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ABSTRACT

This study explored the usefulness of an approach to science instruction which specifically considered children's spontaneous conceptions about natural phenomena. The aim of the instruction was the development of conceptual understanding. The instructional approach involved diagnosing children's spontaneous conceptions, making them aware of their conceptions, having the children discuss their conceptions, having them test their conceptions, and bringing children to a more scientific understanding in light of their instructional experiences. Special attention was paid in the study to the history of science as a heuristic for predicting children's spontaneous conceptions and as a resource for helping children to develop a more scientific understanding and a better understanding of science. The study was conducted in a grade six Canadian elementary classroom. The science content was a unit on optics selected by the classroom teacher. Data were collected through pencil-and-paper evaluations, interviews, daily response journals, and taped recordings of student discussions. In the data analysis consideration was given both to the overall changes in understanding of the whole class and to the specific changes in understanding of three individual students. Materials for the test and instruction are appended. (Author/YP)

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Teaching Science for Understanding
Implications of Spontaneous Conceptions and the History of Science

by Dougal MacDonald

A Thesis Submitted to the Faculty of Graduate Studies in Partial Fulfillment
of the Requirements for the Degree of Master of Arts

Faculty of Education
Department of Curriculum and Instruction

Calgary, Alberta
September, 1989

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Teaching Science for Understanding", submitted by Dougal Alan George MacDonald in partial fulfilment of the requirements for the degree of Master of Arts.

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Abstract

This study explores the usefulness of an approach to science instruction which specifically takes into account children's spontaneous conceptions about natural phenomena. The aim of the instruction is the development of conceptual understanding. The instructional approach involves diagnosing children's spontaneous conceptions, making children aware of their conceptions, having children discuss their conceptions, having children test their conceptions, and bringing children to a more scientific understanding in light of their instructional experiences. Special attention is paid in the study to the history of science as a heuristic for predicting children's spontaneous conceptions and as a resource for helping children to develop a more scientific understanding and a better understanding of science..

The study was conducted in a Grade Six classroom with an extant class. The science content was a unit on optics selected by the classroom teacher. Data were collected through pencil and paper evaluations, interviews, daily response journals, and taped recordings of student discussions. In the data analysis consideration was given both to the overall changes in understanding of the whole class and to the specific changes in understanding of three individual students.

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Knowledge is the reflection of nature by man. But this is not a simple, not an immediate, not a complete reflection but the process of a series of abstractions, the formation and development of concepts, laws, etc., and these concepts, laws, etc. (thought, science = "the logical idea") embrace conditionally, approximately, the universal law-governed character of eternally moving and developing nature.

(V. I. Lenin)

Left to their own devices, students may discover many interesting things about plants or light, but they will develop scientific ideas about photosynthesis or vision about as rapidly as the human race: in other words, not in a single lifetime.

(Charles Anderson)

Understanding requires an act of participation, a conscious act of finding out.

(H. S. Bains)

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CHAPTER ONE

INTRODUCTION

This study was inspired by a desire to improve science instruction. It was noted that learning in science, as in other subject areas, is often still characterized by the memorization of facts and the regurgitation of those facts on tests (White and Tisher, 1986). These memorized facts are not retained over time. Even when certain facts are memorized, there is little evidence of a deeper conceptual understanding, that is, facts are memorized as discrete pieces of information and are not integrated into a deeper conceptual understanding (Minstrell, 1989). Thus, basic concepts in science are not thought through and grasped in a meaningful way. "As we know from investigations of the process of concept formation, a concept is more than the sum of certain associative bonds formed by memory, more than a mere mental habit; it is a complex and genuine act of thought that cannot be taught by drilling" (Vygotsky, 1962, p. 82). Important evidence of a lack of conceptual understanding is the inability of students in many cases to transfer and apply scientific conceptions to new examples (Minstrell, 1989). The aim of this research, then, is to explore an approach to science instruction through which children might develop a better conceptual understanding in science and thus a better understanding of natural phenomena. "Practical experience also shows that direct teaching of concepts is impossible and fruitless. A teacher who tries to do this usually accomplishes nothing but empty verbalism" (Vygotsky, 1962, p. 83). Specifically, it is thought that in trying to develop such an approach, one key consideration is taking into account children's "spontaneous conceptions" and how these conceptions change during instruction.

SPONTANEOUS CONCEPTIONS

Recent research in science has shown that what children bring to science learning is not a tabula rasa or "blank slate". Children's brains are not just clean pages upon which new learning is written, not just empty vessels waiting to be filled. Instead, children in science classes already have spontaneous conceptions (Vygotsky, 1962). "Piaget draws a sharp line between the child's ideas of reality developed mainly through his own mental efforts and those that were mainly influenced by adults; he designates the first group as spontaneous" (Vygotsky, 1962, p. 84). These ideas are developed by children in the course of their experiences with nature. They are ideas by which children attempt to explain the natural phenomena which constitute their world. Children's spontaneous conceptions are almost always different from scientific conceptions, that is, from currently accepted explanations for natural phenomena which have been developed over two thousand years of human thought and science. Many studies on spontaneous conceptions, also referred to as "misconceptions" (Helm, 1980, cited in Gilbert and Watts, 1983), "alternative conceptions" (Driver and Easley, 1978, cited ibid.), and "preconceptions" (Novak, 1977, cited ibid) are cited in the body of this thesis. The reader is particularly referred to several summaries of a number of studies undertaken by researchers in various areas of science: Driver and Erickson, 1983; Gilbert and Watts, 1983; Driver, Guesne, and Tiberghien, 1985; Hashweh, 1988; and, Shymansky and Kyle, 1988. The above research shows that children bring into the science classroom their own conceptions of the answers to such scientific problems as how light travels, how we see, what the shape of the earth is, how objects move, and so on.

Because of these spontaneous conceptions, traditional science instruction may need to be reassessed. Traditional science instruction has been based on the idea that children are simply more or less passive receptacles of factual knowledge, who take in the knowledge dispensed by the teacher (Anderson, 1987). Teachers transmit the concepts and processes of science as facts, and students assimilate them. The view that students have spontaneous conceptions previous to science instruction suggests that science teachers are dealing with active rather than passive minds, minds which already hold to certain views which will influence the way in which they perceive what the teacher is trying to put across. In other words, it is by no means given that the students will "see" what is being taught in the science class the same way that the teacher does, nor that the students will accept what is being taught in the form in which the teacher presents it. The existence of spontaneous conceptions may be a critical barrier which, if not taken into account, will prevent children from achieving a better understanding.

Spontaneous conceptions have some common characteristics which many researchers have identified (Driver, Guesne, and Tiberghien, 1985).

1) Spontaneous conceptions are strongly and intelligently held. Even though they may not correspond to current scientific thinking, they are consistent with the students' everyday experience. That is, the students' spontaneous conceptions provide the students with perfectly reasonable explanations of the natural phenomena which they encounter. Since they have an explanation which is satisfactory to themselves, the students then "think they know". Thus, they see no need to change their conceptions (DiSessa, 1982; Ault, 1984; Anderson and Smith, 1986).
2) Spontaneous conceptions are not merely isolated facts but are part of a larger grouping of spontaneous conceptions (Nussbaum and Novak, 1976; Osborne and Gilbert, 1980; Clement, 1982; Driver, 1983;

McCloskey, Washburn, and Felch, 1983). Thus, correction of a few facts will not likely be sufficient to change a spontaneous conception. New facts may simply be fitted into the extant network of concepts and cause no significant change. The instruction must be more comprehensive, that is, must be designed to deal with a larger grouping of connected concepts, must "get to the bottom of the matter".

3) Spontaneous conceptions which are not in accord with scientific conceptions can interfere with formal science instruction (Anderson, 1983; Driver, 1983; Minstrell 1989). Because the students have no reason to believe their views are inadequate, they tend to assimilate new knowledge without changing their conception. That is, they are able to "fit" their new learning into their spontaneous conception, and to use it, not to call into question their spontaneous conceptions, but rather to support them. Accommodation, the changing of their conception in light of the new learning, does not take place. In reading a science textbook, for example, they "change" the textbook to fit with their held view, rather than changing their held view to fit with what the textbook is saying (Roth, cited in Anderson, 1987).

Children hold spontaneous conceptions because, like all human beings, as they have experiences, they try to explain them. These explanations are based mainly on the child's own commonsense reasoning applied to perceptions about the physical world (Shanon, 1976; Champagne, Klopfer, and Anderson, 1980; Clement, 1980; Caramazza, McCloskey, and Green, 1981; McCloskey, Washburn, and Felch, 1983; McCloskey and Kohl, 1983; Eaton, Anderson, and Smith, 1984; Driver, Guesne, and Tiberghien, 1985). Such explanations are necessary for the child to interact with her environment in an efficacious way and to make sense of her experiences. The explanations arrived at are those which are adequate to allow the student to describe and to function in the everyday world. They represent the manner in which the child feels that the natural world operates. Because of their origin, spontaneous conceptions operate in a less integrated fashion than scientific knowledge, focussing on gross situational cues and expectations rather than specific details. Spontaneous conceptions have a loose structure, show little interconnectedness, and lack an overlying formalism. In this way, even though they are adequate for the child's everyday experience, they differ markedly from comprehensive scientific theories. But, while spontaneous conceptions do not represent a formal, coherent theory in a scientific sense, they do form a conceptual entity which serves the student in situations outside classroom instruction. There are enough pieces and enough connections to deal sensibly with most everyday experience. Thus, when classroom instruction conflicts with spontaneous conceptions, the latter will often be coherent enough to mitigate the "classroom version of events". This is the sense in which it is meant that spontaneous conceptions may create barriers to science instruction.

Spontaneous conceptions in science have parallels with the historical development of science. Many researchers have noted that the spontaneous conceptions of students often correspond to outdated views once held by leading scientists through history (Shanon, 1976; DiSessa, 1976; Caramazza and Green, 1981; Clement, 1982; Nussbaum and Novick, 1982; McCloskey et al., 1983; Ault, 1984; Prather, 1985; Wandersee, 1985). For example, a student may initially hold an Aristotelian conception of motion, then come to slowly replace that with a Newtonian conception (DiSessa, 1982). Many other examples of this parallel with history can be cited. "The historical persistence of these beliefs suggest that they are a natural outcome of experience in the world" (Caramazza, McCloskey, and Green, 1981). In other words, the development of science conceptions held by the student may parallel to a certain extent the historical development of scientific conceptions in the society. The history of science, then, may provide an important heuristic in helping teachers both recognize and alter spontaneous conceptions. Knowledge of science history will assist teachers in determining what spontaneous conceptions the student may hold, the nature of those spontaneous conceptions, and how the student may be encouraged to develop a more scientific conception. (Berger, 1968; Klopfer, 1964, 1969; Wandersee 1985).

INSTRUCTION

Given that children's spontaneous conceptions are a natural outcome of experience; are strongly held; are part of a larger grouping of incorrect conceptions; and can interfere with the understanding of scientific conceptions, there is a need for science instruction to take them into account. Further, since spontaneous conceptions are often incorrect, attempts must be made to move children toward more scientific conceptions. This can be best done through instruction. "Left to their own devices, students will discover many interesting things about plants or light, but they will develop scientific ideas about photosynthesis or vision about as rapidly as the human race: in other words, not in a single lifetime" (Anderson, 1987, p. 86). At the same time, this instruction must be designed to take into account the spontaneous conceptions which the child holds (Vygotsky, 1962). This strikes a balance between the totally child-centred view where anything the child thinks is acceptable as is, and the totally instruction-centred or teacher-centred view, where only the scientific conception is important and the spontaneous conception of the child is irrelevant. On the one hand, the totally child-centred view leads to accepting any conception as "correct", while, on the other hand, the totally instruction-centred or teacher-centred view leads back to the extreme of information transmission by the teacher into the passive, "empty vessel" of the student's mind.

Vygotsky explains why both the child's spontaneous conceptions and the scientific conceptions developed by human knowledge are important in instruction. According to Vygotsky, the child naturally acquires spontaneous conceptions in the course of experience. These interact with conceptions acquired through instruction, developing into a total system of concepts. Both the individual's experience in the world and formal knowledge, the knowledge acquired by society over many centuries, are necessary to understanding natural phenomena. The child is unaware of her spontaneous conceptions; it is instruction which brings about awareness, indicated by the ability to generalize. Although instruction is the key to understanding, a certain level of spontaneous conceptions is needed for the instruction to be fruitful. "We believe that the two processes, the development of spontaneous and non-spontaneous concepts, are related and constantly influence each other. They are parts of a single process, development of concept formation, which is affected by varying external and internal conditions but is essentially a unitary process, not a conflict of antagonistic, mutually exclusive forms of mentation" (Vygotsky, 1962, p. 85).

CONCEPTUAL CHANGE

The notion that instruction should be designed to guide students to more scientific conceptions implies some type of conceptual change (Posner et al., 1982; Hashweh, 1986). When exposed to scientific concepts which conflict with their spontaneous conceptions, students tend to either assimilate or accommodate (Piaget, 1970). That is, as previously noted, students will either adapt new learning to fit in with their previous conception or they will alter their conception in light of the new learning. When students' conceptions are essentially scientific, assimilation is a good strategy. The new learning further develops the students' scientific understanding. But when students' conceptions are not scientific and the aim of instruction is to help students achieve a more scientific understanding, assimilation is a bad strategy. What is required is accommodation, an alteration of the held conceptions in light of the new learning. It is accommodation to a more scientific understanding that science instruction should be designed to bring about when students' conceptions are not scientific, as is usually the case. There are many factors which naturally tend the student toward assimilation, from the functionalism of normative attitudes to outside social and classroom conditions (Ross and Lepper, 1980; Alcock, 1981; Bunge, 1983). There are also a number of conditions and strategies which can encourage accommodation, from empirical testing to metacognition (Alcock, 1981; Posner et al., 1982; Bunge, 1983; Hashweh, 1986; Shuell, 1987). The main task of instruction, then, becomes one of encouraging accommodation to the new learning. Instruction should be designed with that general purpose in mind.

DESIGNING INSTRUCTION

The design of science instruction, then, begins from serious consideration of the student's spontaneous conceptions because these will influence how the student approaches the new learning. The general aim of instruction is to bring about conceptual change toward a better understanding of natural phenomena, that is, to help the student to move from her spontaneous conceptions toward more scientific conceptions. This does not mean "extinguishing" the spontaneous conceptions but building on them. It means helping the child to restructure her extant knowledge in light of a more scientific understanding (Vosniadou, 1988). "The act of instruction can be viewed as helping the student unravel individual strands of belief, label them, and then weave them into a fabric of more complete understanding" (Minstrell, 1989, p. 130). As Vygotsky pointed out, in instruction, both the spontaneous conceptions of the child and the scientific conceptions developed by human thought have their place (Vygotsky, 1962). Neither should be neglected; both should be taken into consideration. "An important point is that later understanding can be constructed, to a considerable extent, from earlier beliefs. Rather than denying the relevancy of a belief, teachers might do better by helping students differentiate their present ideas from and integrate them into conceptual beliefs more like those of scientists" (Minstrell, 1989, p. 131).

If instruction is to bring about better learning, conceptual change should be brought about in such a manner that the students actually develop a better understanding of natural phenomena (Minstrell, 1989). The memorization of a concept as a discrete fact will not result in better understanding. To develop a better understanding, teachers must encourage students to actively and consciously participate in learning. In science education and in education in general, particularly in about the last twenty-five years, researchers have devoted time to trying to develop instructional approaches which help contribute to active and conscious student involvement in learning. These "approaches for understanding" include discovery and inquiry methods in science (Shulman and Kesler, 1966; Pella, 1968; Carin and Sund, 1975; Gohau, 1980), the teaching of thinking based on cognitive processes (Lawson and Lawson, 1979; Novak, 1979; Osborne and Wittrock, 1983; Collins, 1984; Carey, 1986; Minstrell, 1986; Baron and Sternberg, 1987; Vosniadou, 1989), and the use of teacher-student and student-student dialogues (Finegold, 1974; Paul, 1984, 1987). It is important to couple the teaching approaches developed through the above research with the notion of spontaneous conceptions. Otherwise, the spontaneous conceptions approach may simply become a more efficient way of memorizing concepts and the main goal of understanding will be lost. Further, students who are encouraged by instruction to actively and consciously participate in scientific inquiry, will have the opportunity not only to attain a more scientific understanding of natural phenomena, but also to attain a better understanding of what science is and how it is conducted. This may, in turn, motivate them to undertake further learning outside the confines of the class, certainly a very desirable outcome.

The history of science can be of direct assistance in designing science instruction which begins from students' spontaneous conceptions. It can help in discovering what spontaneous conceptions students might hold because students' spontaneous conceptions are often found to have parallels with the history of science (Wandersee, 1984). Attention to the history of science can also aid in illuminating the nature of science for both teachers and students. For example, historical changes in human ideas about natural phenomena demonstrate that scientific knowledge is corrigible and mutable. The history of science can assist in maintaining the intellectual confidence of students. Students may be brought to realize that there is no stigma attached to holding inadequate or erroneous ideas by becoming aware of the course of historical changes in scientific theories. Theories that were once put forth by great thinkers have been found to be inadequate or misleading and have been developed or discarded in the light of further scientific work (Ault, 1984; Prather, 1985).

To evaluate instruction for understanding, evaluation methods must be used which can investigate the process of reconceptualization as well as the products, and which can probe for deep understanding rather than just possible rote memorization. That is, if science instruction which brings about a deeper conceptual understanding is to be meaningfully evaluated, ways must be developed which can distinguish between scientific conceptions which are memorized as part of the "school game" and scientific conceptions which actually represent a better understanding by the student of natural phenomena. The statement of a scientific conception is not necessarily an indication of a better understanding. Evaluation of student learning for understanding during instruction can be based on listening to student ideas and listening to student questions. Following instruction, possible ways of evaluating understanding rather than memorization are having students try to explain their conceptions to others and having students try to transfer and apply their learning to new and unfamiliar problems and situations.

Instruction must be designed with the realities of the regular classroom in mind. An approach to instruction which places unrealistic demands on teacher and classroom has little chance of succeeding. Teachers must work under certain conditions, such as time press, a large group of students, availability of materials, acceptable evaluation methods, and so on (Feiman-Nemser and Floden, 1986). These realities must be taken into consideration when attempting to develop new instructional approaches. Although one of the purposes of a new approach to instruction may precisely be to begin altering some of the conditions which contradict it, it would be unrealistic to expect that comprehensive changes in the nature of school classrooms will take place rapidly over a short period of time. If an instructional approach requires wide-ranging changes in what teachers do, it may be treated as more of a hindrance than a help. This will lessen its chances of being adopted by teachers as an approach which could be of use in the classroom.

In general, one instructional design in light of spontaneous conceptions involves finding out what children's individual spontaneous conceptions are, making them aware of their spontaneous conceptions through discussion and debate, having students test their conceptions through a process of inquiry in order to find evidence which supports them, analyzing the results of the testing, provoking cognitive conflict between students' initial conceptions and the scientific conception, and trying to bring the student toward a more scientific understanding (Driver and Erickson, 1983). Ample opportunity should be given for students to question (Nussbaum and Novick, 1982), to test, and to transfer and apply their new understanding to new problems and situations (Minstrell, 1989). Throughout instruction, it should always be kept in mind that the process of reconceptualization, if it is to be based on understanding, may occur over a long period of time (Driver, 1983).

In Chapter Two, the relevant literature on children's conceptions, the nature of science, the nature of instruction, conceptual change, and the design of instruction will be reviewed.

CHAPTER TWO

REVIEWING THE LITERATURE

SPONTANEOUS CONCEPTIONS

A great deal of research has been done recently on spontaneous conceptions (also called "misconceptions", alternative conceptions", and "preconceptions") in science. Tisher and White (1986) note that numerous studies on the understanding of particular scientific concepts and rules began to appear in the mid-70's. They suggest that possible reasons for this were the rise of cognitive science and the perceived need to relate science more to everyday life. The research on conceptions has had two main phases. It began with the development of techniques to assess children's understanding of science concepts. This was followed by attempts to design instruction to bring children to a more scientific understanding. These latter attempts are still going on. Tisher and White (1986) and Driver (1983), among others, suggest that changing children's spontaneous conceptions may be difficult. The conditions required for conceptual change could be summarized as follows: "The learner must be dissatisfied with his or her existing conception, and must find the new conception intelligible, plausible, and fruitful" (Posner, Strike, Hewson, and Gertzog, 1982). Such general guidelines must be developed into specific instructional strategies to be useful. Thus, it is important to continue research into how changing spontaneous conceptions might be best achieved.

The literature on spontaneous conceptions is large. Some partial summaries have been made by Gilbert and Watts (1983), Driver and Erickson (1983), Linn (1986), Tisher and White (1986) and Shymansky and Kyle (1988). A limited review of some typical studies will be made for the purpose of demonstrating the existence of spontaneous conceptions over a large number of science topics. This is important because the rationale for the study is precisely this claim. These studies as a whole also draw more specific conclusions about spontaneous conceptions, including their diagnosis, universality, nature, origin, and parallels with the history of science. These conclusions lead to important implications for instructional design. The studies in the review are grouped according to their topic, for example, force and motion, earth and gravity, light, plant studies, and so on.

Force and Motion

Shanon (1976) investigated whether "models underlying the perception and interpretation of kinematic phenomena are Aristotelian or Newtonian", in the sense that according to Aristotle bodies fall at a constant speed whereas according to Newton bodies fall with a constant acceleration independent of mass. Of 140 responses, Shanon classified 77.8% as Newtonian and 7.1% as Aristotelian. He noted that this revealed a discrepancy between everyday models of the world and scientific models, a difference he attributed to the tendency of people to rely on perception for explanations of natural phenomena, rather than cognition.

Champagne, Klopfer and Anderson (1980) looked at what factors influenced the learning of mechanics. In a pretest, most students revealed a poor understanding of Newtonian concepts of motion. However, each student did have "a rich accumulation of interrelated ideas that constitute a personal system of common-sense beliefs about motion". It was noted that these conceptions were adequate for students to describe the natural world of their experience. The pre-instructional belief system held by the students had many parallels with physics from an Aristotelian point-of-view, although not precisely, since it was under-developed, loosely structured, showed little interconnectedness, and was ultimately highly flexible. The researchers noted that the Newtonian view, which was the aim of formal instruction, presumed an idealized natural world, an abstract, frictionless world not found in everyday experience.

Caramazza, McCloskey, and Green (1981) studied the beliefs of university undergraduates about projectile motion. Three-quarters of the students had received formal physics instruction at least at the high school level and about 1/4 had taken some college physics. The students were asked to predict the path taken by a ball on a string swinging in a pendulum-like arc, depicted in line drawings, if the string was cut at a particular, designated location. Only about 1/3 of the subjects produced correct responses. The majority of students demonstrated naive beliefs related to a pre-Galilean model of motion. It was noted that formal physics instruction seemed to have played some role in providing some students with a better understanding of projectile motion.

DiSessa (1982) investigated students' grasp of Newton's first law of motion, which states that when a force is applied to a moving object, the vector change in the velocity of the object is proportional to the force and inversely proportional to the mass of the object. The students used a computer graphics simulation called a dynaturtle, an ancestor of the Logo geometry turtle, which moved on the screen in response to student commands typed at a keyboard. The dynaturtle represented Newton's law by moving forward in a straight line unless otherwise commanded. The students were instructed to command the turtle to change direction onto a new path which would cause it to strike a predetermined target at a minimal speed. DiSessa found that at first all the students tried to make the moving turtle turn sharply 90 degrees toward the target, a strategy in line with the Aristotelian idea that things simply continue on the direction you push them. In other words, the students did not take into account either forward motion or mass. Over time, most children developed strategies through trial and error which allowed them to better satisfy the conditions of the experiment. DiSessa noted that the advantages the computer simulation had over the "real world" was that it eliminated everything from consideration except the specific problem, and that it was a frictionless environment. The "real world" is non-Newtonian because friction acts; Newton's law separates friction as a force to be added to the analysis. In other words, dynaturtle, unlike the real world, is a pure representation of Newton's laws, so it leads to different conclusions than experience in the real world. Clement (1982) also found students had problems understanding the relationship between force and acceleration as set out by Newton's law.

McCloskey, Washburn, and Felch (1983) examined the nature and origin of the "straight-down belief", the idea that an object carried by another moving object, for example, a ball carried by a moving person, will fall straight down when dropped. Actually, it will fall in a parabolic arc. Newtonian mechanics points out that this is because after the ball is released it continues to move forward at the same speed as the walker, as well as downward due to gravity. Out of 99 undergraduates, both physics-trained and untrained, less than half stated the ball would move forward. Students without physics training gave more straight-down responses than students with physics training. Similar results were obtained with related problems. The origin of the straight-down belief is attributed to the fact that objects dropping from moving carriers are perceived by the eye to fall straight down.

McCloskey and Kohl (1983) examined the curvilinear impetus belief. College students were asked to draw the path taken by a metal ball being whirled above a person's head, when the string holding the ball broke. The scientifically correct answer is that the ball will travel in a straight line in the direction it was moving when the string broke. About 30% of the students drew a curved path. McCloskey and Kohl attributed this erroneous view to a belief that the ball had acquired curvilinear impetus by being whirled in a circle, and that this motion was carried on when the string broke. This belief was thought to originate in everyday situations where people observe and interact with moving objects such as rotating tops, rotating wheels, or spinning balls. Observations of how rotating objects move, that is, they continue to move for some time after being set in motion, may be extrapolated to objects moving in a curved path, that is, they too will continue to move after being set in motion but in a curved rather than a straight path.

Earth and Gravity

Nussbaum and Novak (1976) and Nussbaum (1979) investigated children's conceptions of the earth. They noted that it was impossible to isolate the idea of the earth from related ideas of distance, space, force, gravity, and so on. "To attempt to isolate a 'pure' concept for instruction is to check out of the game of science education" (Nussbaum, p. 536). Second grade children were first interviewed in order to bring out their individual conceptions. They were then given tasks to predict the direction of imaginary free fall at different points on the earth model, and to explain the basis of their predictions. Nussbaum noted that although children stated they had been told the earth was a sphere, and some even articulated this explanation, many children's actual predictions assumed a flat earth. This, he felt, accorded with their immediate sense perceptions of the shape of the earth which they had acquired from living on it. Mali and Howe (1979) replicated

Nussbaum and Novak's work in a cross-cultural study with Nepalese children and had similar findings.

Heat

Erickson (1980) examined grade 5, 7, and 9 children's views about heat. The children were given brief, written descriptions of the results of simple experiments with heat, then asked to assess the best explanation for the phenomena from a scale of alternatives. The scale was actually made up of six scales relating to agreement, clarity, ease of understanding, truth, familiarity, and similarity to the students' ideas. Children's views were compared with the current scientific view of heat (Kinetic Viewpoint), the earlier scientific view of heat (Caloric Viewpoint, which saw heat as a substance), and the Children's Viewpoint, a collection of ideas found to be common to many children in a previous study (1979). The Children's Viewpoint included ideas such as "a large rod heats up faster than a small one because it has more air spaces in it for the heat to travel through", "a whole rod heats up because when one part cannot hold any more heat the heat moves further along the rod", "wax melts because it is soft", and "metal cubes become hotter when heated than wood or sugar because it is more difficult for air to get into hard metal to cool it". Erickson found that the intuitive ideas of what he labelled the "Children's Viewpoint" were very prevalent among children of all ages, but that there seemed to be a gradual shift with age to the more abstract scientific conception, which Erickson labelled the "Kinetic Viewpoint".

Light

Eaton, Anderson, and Smith (1984) examined Grade 5 students' conceptions about light. From a pretest, they determined that the students had the incorrect conception that we see things because light brightens objects, rather than we see objects because light is reflected off them to our eyes. (The former was Plato's view, the latter held by the Stoics and later by Al-Hazen in the 13th century). Further, during formal instruction of the unit, the students were able to readily assimilate other concepts of the unit, such as light travels very fast and light travels in straight lines while still retaining their incorrect conception about how we see. This assimilation occurred even though the researchers felt that the role of reflected light was the most important concept in the unit. Thus, not only were the students initially strongly committed to their initial conception, they also managed to reinforce it throughout the unit.

Plants/ Photosynthesis

Smith and Anderson (1984) investigated Grade 5 students' understanding of photosynthesis and plant growth. The major ideas under consideration were (a) that green plants use food stored in the seed to begin to grow, and (b) that after this food is used up they must have light in order to make food and survive. The teacher hoped that from the results of an experiment which compared growing plants in light with growing plants away from light, students would induce the idea that plants cannot survive in the dark because they must have light to make their own food. Instead, because the plants in the dark did grow to some extent before they died, many students concluded that light was not necessary but only made plants grow better. This conclusion was reached, even though before the unit most of the students had expressed the idea that plants need light to live and grow. In other words, their observations lead students to an incorrect conclusion rather than a correct one. Smith and Anderson attributed this result basically to the failure of the teacher to make a timely introduction of the idea of photosynthesis, expecting instead that the students would induce this idea on their own from the experimental evidence.

Other Spontaneous Conceptions

Numerous other studies have been done on spontaneous conceptions in science. These include both other studies done on the topics mentioned above, plus studies on other topics such as human circulation, buoyancy, ions, ecology, electricity, heredity, cell theory, particulate theory, the mole, gases, chemical equilibrium, acids and bases, pseudoscience, air and air pressure, and energy. Lists have also been developed comparing scientific conceptions with spontaneous conceptions. For example, Nussbaum and Novik (1982) noted a number of conceptions accepted by current science and the concomitant spontaneous conceptions. These include matter as particulate vs matter as continuous; Newtonian mechanics vs. Aristotelian mechanics; heat as energy vs. heat as substance; Einstein's notions of space and time vs. Newton's notions; statistical models vs. mechanical models (in the atomic theory, genetics, etc); a spherical earth vs. a flat earth; heliocentric cosmology vs. a geocentric one; and a mechanistic approach to biology vs. a vitalistic one. There is a vast amount of data available at present on the existence of spontaneous conceptions.

Researchers agree, then, that spontaneous conceptions are universal across a wide variety of science content areas. They also agree on several important features of these conceptions, which have important implications for instructional design.

1) Spontaneous conceptions are relatively stable in the face of traditional formal instruction. In other words, they are "intelligently held" (Ault, 1984). (Driver and Erickson, 1983; Eaton, Anderson, and Smith, 1984; Smith and Anderson, 1984; Prather, 1985; Clough and

Wood-Robinson, 1985; Driver, Guesne, and Tiberghien, 1985; Anderson, Sheldon, and DuBay 1986; Anderson and Smith, 1986).

2) Spontaneous conceptions are not isolated facts but are part of a larger, loose network of ideas which help to support each other, although not necessarily in a "logical" fashion (Nussbaum and Novak, 1976, 1979; Clement, 1979; Osborne and Gilbert, 1980; Champagne, Klopfer, and Gunstone, 1982; Ault, Novak and Gowin, 1984; Driver, Guesne, & Tiberghien, 1985; Terry and Jones, 1986).
3) Spontaneous conceptions, when incorrect, interfere with the acquisition of new knowledge. Often new knowledge is simply assimilated without causing any change in the spontaneous conception (Ault, 1980; Driver and Erickson, 1983; Eaton, Anderson, and Smith, 1984; Appleton 1985; Arzi, 1985; Prather, 1985; Hewson, 1986; Fisher and Lipson, 1986;).

A number of researchers have attempted to explain why spontaneous conceptions exist. These explanations fall into three general categories.

1) By far the most common explanation is that children draw conclusions about natural phenomena based on sense experience in the everyday world. Shanon (1976) believes children rely more on perception than cognition. Champagne, Klopfer, and Anderson (1980), Caramazza, McCloskey, and Green (1981), and McCloskey, Washburn, and Felch (1983) see "naive physical laws" as developing from everyday experience with objects. Clement (1980) and DiSessa (1982) see spontaneous conceptions as arising from experience with objects in the real world, whereas scientific conceptions, such as Newton's laws, imply a frictionless, ideal world outside of experience.

Eaton, Anderson and Smith (1984) attribute spontaneous conceptions to the tendency of human beings to make assumptions about the way the world works. Driver, Guesne, and Tiberghien (1985) refer to the thinking which gives rise to spontaneous conceptions as "perceptually-dominated", "linear-causal", and "context-dependent". Hewson (1986) states that students acquire spontaneous conceptions about density as a result of everyday experiences which clash with current scientific thinking. Hashweh (1988) states that "many researchers agree that most 'preconceptions' arise as a result of experience in interacting with the world". Andersson (1986) sees a common core across spontaneous conceptions which he calls "the experiential gestalt of causation". This involves direct contact among agent, instrument, and object as a necessary condition for change.

2) Poor instruction was also cited as a factor in evolving spontaneous conceptions. Adeniyi (1985) and Shuell (1987) surmise that further erroneous conceptions may be introduced to students during instruction. Anderson, Sheldon, and DuBay (1986) declare that some of students' spontaneous conceptions are actually memorized facts disconnected from understanding. Driver (1983) and Joshua and Dupin (1986) note that the traditional inductivist approach to classroom experiment, with its emphasis on observation, may lead to several contradictory hypotheses. Sere (1986) sees spontaneous conceptions as deriving both from everyday experience and from observations made during classroom experiments.

3) Social ideology was also noted as a factor. Fisher and Lipson (1985) feel that spontaneous conceptions arise from experience in the everyday world plus a common cultural heritage. In other words,

> children have common experiences with natural phenomena and, because of the beliefs of the society in which they live, tend to interpret these experiences in particular, but similar ways.

A number of studies show parallels between spontaneous conceptions and the history of science. Shanon (1976) and DiSessa (1982) describe notions about motion as Aristotelian and Newtonian. Clement (1980) refers to Galilean and Newtonian views in his study of acceleration. Ault (1984) mentions Newtonian time. Caramazza, McCloskey, and Green (1983) refer to "pre-Galilean models". Ben-Zvi, Bat-Sheva, and Silberstein (1986) point out that students' erroneous views about atoms "place them in the Greek period". Hashweh (1988) summarizes the relationships between the findings of a number of force and motion studies, on the one hand, and science history, on the other hand. Nussbaum and Novick(1981) also see a parallel with the history of science. Driver, Guesne, and Tiberghien (1985) see a parallel with the history of science, but caution against pressing it too far, since children's spontaneous conceptions are not as coherent and consistent as historical theories. Wandersee (1985) carried out a detailed study of 1405 students which compared the historical development of the photosynthesis concept with children's spontaneous conceptions. He concluded that "students do not merely recapitulate the history of science in learning the photosynthesis concept. Yet, it is evident that the misconceptions of the past can be found in the conceptual frameworks of today's students" (p. 594).

INSTRUCTION

It is important that students work toward learning correct scientific conceptions. To declare otherwise would be a caricature of child-centred education, a promotion of the extreme view that whatever the child thinks or does on her own is fine, that individual induction from experience in whatever direction is enough. This view leads to the teacher having no interventionist role to play in the classroom. Further, to declare that learning scientific concepts is not important would be to negate the two thousand year history of the development of human scientific thought. Of course, this does not mean that every child must or can be immediately taught every detail of every up-to-date scientific theory. Far from it. This would be like answering a child's question about how a car works by going into every detail of every circuit, mechanism, and chemical reaction. What it means is that the teacher must take responsibility for bringing the child to a clearer and deeper understanding of scientific concepts than previously held. In this endeavour, the teacher tries to follow sound pedagogical principles by keeping in mind both what the child already understands and what the child is capable of understanding.

Instruction can help children move toward a better understanding of scientific conceptions and thus of natural phenomena by taking into account both the child's spontaneous conceptions and the current scientific view. Vygotsky (1962) saw the developing child as acquiring basically two kinds of concepts. Spontaneous concepts are those developed mainly through the child's own efforts. Scientific conceptions are decisively influenced by adults, for example, by parents and teachers. These two kinds of concepts interact and unite into a total system of concepts. Both are necessary because, on one hand, spontaneous concepts are acquired naturally in the course of human experience in the natural world. On the other hand, it is impossible for every human being to have every experience and thus to acquire the total sum of human knowledge by direct experience. "When we impart systematic knowledge to the child we teach him many things that he cannot directly see or experience" (Vygotsky, 1962, p. 86).

Vygotsky saw generalization, the ability to subsume a concept as a particular case under a more encompassing concept, in other words to see it as part of a system, as the signpost of awareness of a concept. As an example of non-awareness, he gives the example of a child who, when asked, "Do you know your own name?", answers by giving his own name, instead of answering, "Yes, of course". Spontaneous concepts are those of which the child has no awareness. The main force in bringing about awareness, according to Vygotsky, is instruction, more specifically, school instruction based on the total sum of human knowledge. The contact with scientific concepts in school begins the process of systematization, which is transferred to the spontaneous concepts. These are restructured "from the top down". Vygotsky attaches great importance to instruction, seeing it as the most important factor in learning. At the same time, he states that, for a scientific concept to be absorbed, the development of a spontaneous concept must have reached a certain level. "One might say that the development of the child's spontaneous concept proceeds upward and the development of the scientific concept proceeds downward" (p. 108). Scientific concepts "supply structures for the upward development of the child's spontaneous concept toward conscious deliberate use" (p. 109). New generalizations can be built on generalizations of a lower level. Both spontaneous and scientific conceptions are necessary to children's learning.

CONCEPTUAL CHANGE

Since science instruction is designed to move the child from her spontaneous conception to a more correct scientific conception, a process of conceptual change is implied. In general, conceptual change can be seen from the viewpoint of assimilation vs accommodation (Piaget, 1970). In assimilation, new knowledge is fitted into existing conceptual structures. In accommodation, new knowledge results in the alteration or replacement of extant conceptual structures. In each case, assimilation or accommodation, the aim of the child is to make sense of the world. Schema theory makes the assimilation-accommodation model more specific (Hashweh, 1986). Cognitive psychology sees knowledge as being organized into structural units called "schema". A schema is an abstraction from previous experience which represents some part of the world. It is composed of the elements of this representation plus their interrelationships. Understanding is seen as an act whereby certain schema are "mapped" onto the particular situation encountered. Since the aim of science instruction in relation to spontaneous conceptions is to move the child closer to a correct scientific conception, this implies that instruction must bring about accommodation, rather than assimilation, that is, must bring out the inadequacy of present schema. Instruction must be designed so that instead of the new learning being simply assimilated, the new learning causes the alteration of extant conceptual structures. Since research shows that often traditional formal instruction is insufficient to accomplish this, it is reasonable to conclude that science instruction needs to be at least partially redesigned in light of our knowledge of the existence of spontaneous conceptions. The specific process which must be gone through to move students to a more scientific conception involves them in examining their spontaneous conceptions, considering the scientific conceptions, resolving any conflict between the old and the new in light of evidence, and making the new conceptions available for further application. In light of the above, it is important to try to identify the factors which affect the persistence of spontaneous conceptions, the factors which affect acquisition of new scientific conceptions, and the factors which affect cognitive restructuring (Hashweh, 1986).

There are a number of internal factors which generally contribute to the persistence of extant schema, that is, which favour assimilation. They include the fact that the normative view is appropriate to daily living, i.e., continuous questioning of all schema is dysfunctional; that an individual's knowledge exists within a supporting network; that confirmation for extant schema is more likely than disconfirmation because new data is evaluated in light of old data, that is, data which confirms is more likely to be deemed relevant, hypotheses are often not tested, anomalies can be considered as special cases (compartmentalized), and ambiguous data tends to be looked at as confirming; spontaneous conceptions are adequate for certain purposes and for a limited domain of interaction with the world; spontaneous conceptions take the form of procedural knowledge through continuous use and thus become automatic and hard to alter (Ross and Lepper, 1980; Bunge, 1983; Shuell, 1987; Hashweh, 1986). There are also a number of external factors which affect the degree of assimilation. These are found in the society as a whole as well as in classroom life. Societies operate under certain economic conditions, for example, availability of resources for inquiry; societies operate under certain political conditions, for example, degree of tolerance for free inquiry; societies have explicit cultural beliefs and ideology which are reinforced, for example, views of science, religion, myth, and practical lore; societies use certain language which denote commonsense meanings, for example, "sunrise"; and within societies "commonsense" is usually adequate for daily life (Bunge, 1983; Hashweh, 1986). Schools and classrooms also affect the degree of assimilation in certain ways, by enforcing what is practical, for example, inquiry takes "time", and what is important, for example, "coverage of material". Teacher and student knowledge and attitudes also play a role, for example, there are different views of learning and teaching, and different levels of understanding of scientific concepts and of science. (Anderson and Smith, 1983; Hashweh, 1986; Feiman-Nemser and Floden, 1986; Shuell, 1987).

At the same time, ideas, beliefs, and conceptions do change. Mutability is certainly a characteristic of scientific knowledge and none of us hold exactly the same views as we used to. All of us have the ability to learn and are born into a society that keeps some learning tradition. Conceptual changes usually occur slowly and can include fumbling about, false starts, mistakes, and reversals, but such changes can also sometimes occur dramatically (Bunge, 1983). The most important factor in changing conceptions seems to be the relationship between dissatisfaction with the existing conception and the plausibility, intelligibility, potential, and purposefulness of the new conception (Posner et al, 1982; Bunge, 1983). Conditions compatible with conceptual change through accommodation, that is, with the altering or discarding of extant conceptual structures, include exposure to social change, a changing world-view, acceptance of knowledgeable authority, setting of new purposes, appearance of new problems to solve, exposure to experimental results, awareness of anomalies, development of knowledge, and ongoing human curiosity. Accommodation may be stimulated by such general strategies as participating in social change, working with concrete models, making empirical tests, reconsidering evidence, looking though other eyes, dialogue and debate, analogy, metacognition, awareness of the fundamental assumptions of both self and scientific theory, and demand for consistency and simplicity (Ross and Lepper, 1980; Posner et al, 1982; Bunge, 1983; Hashweh, 1986). The purpose of instruction, then, in terms of conceptual change, becomes one of creating conditions whereby accommodation rather than assimilation take place.

DESIGNING INSTRUCTION

The design of science instruction should specifically take into account students' spontaneous conceptions because of the major influence which these conceptions may exert on student learning. Spontaneous conceptions may serve as barriers to learning by encouraging the assimilation of ideas into already held conceptions, rather than the accommodation of already held conceptions to new learning. In order that instruction may begin from the spontaneous conceptions of students, these conceptions must first be determined. Ideally this determination should be before any instruction has taken place. Various methods may be used for discovering these spontaneous conceptions, including written tests (Erickson, 1980; Anderson and Smith, 1986), picture tests, (Osborne and Gilbert, 1980), interviews (Krupa, Selman and Jacquette, 1984), informal questioning, and assessing children's reactions to demonstrations (Nussbaum and Novick, 1982). In this endeavor the history of science may serve as a useful heuristic. That is, if children's spontaneous conceptions to a certain extent parallel the history of the development of ideas in science, then a knowledge of this historical development of ideas in the science area may help both in predicting what conceptions the children may hold and in suggesting appropriate demonstrations and experiments (Wandersee, 1985).

Beginning from the children's spontaneous conceptions, science instruction should encourage conceptual change in the direction of a better understanding of natural phenomena. The learning should not be simply the rote memorization of scientific conceptions but should be a process of acquiring a deeper understanding (Minstrell, 1989). The acceptance of a scientific explanation just because it is "in the book" or is backed by the teacher's authority, is insufficient. Explanations for natural phenomena, spontaneous or scientific, must be thought about and thought through, must be discussed and debated, and must be subjected to experimental and "logical" tests. The teacher cannot simply expect the students to stop thinking one thing and to start thinking another (Minstrell, 1989). The learner must actively "construct meaning" (Osborne and Wittrock, 1983), rather than passively accept what is transmitted by the teacher. If science instruction is to really change students' ideas about natural phenomena, students must be able to restructure their conceptions in such a way that their new conceptions make sense to them. Otherwise, science instruction, even if it starts from students' spontaneous conceptions instead of from, say, the textbook, will only become a more efficient means of memorization rather than an approach which actually brings about a better understanding.

Three important developments toward better science instruction which preceded the work on spontaneous conceptions were discovery and inquiry, the thinking skills movement based on cognitive processing research, and the work on dialogue. All may be considered, in part, as attempts to move away from the perspective of the learner as a passive consumer of knowledge toward the perspective of the learner as an active and conscious participator in learning. For example, Carin and Sund (1973) cite arguments in favour of discovery science such as intellectual potency, intrinsic motivation, learning the heuristics of discovery, student-centering, avoidance of mere verbal learning, and permitting time for assimilation and accommodation. Some of the approaches to teaching which they suggest include having students formulate hypotheses, having students make predictions, and having students respond to and ask questions. Teaching for thinking is seen to have benefits similar to discovery and inquiry. In a collection of writings edited by Baron and Sternberg (1987), for example, various thinking researchers suggest that teaching thinking to children through modelling can help them develop their abilities to seek reasons, to focus on questions, to analyze arguments, to ask and answer questions, to infer, to make judgements, to evaluate the adequacy of information, and in general, to think critically about what they are being taught. Finally, just as seeing the child as a passive learner implies a classroom monologue, seeing the child as an active participant in learning implies a classroom dialogue. Approaches have been developed to encourage dialogue in general (Collins, 1984; Paul, 1984, 1987) and specifically in science (Carin and Sund, 1975; Finegold, 1974, 1976). It is important to keep in mind, then, that developing science instruction in light of spontaneous conceptions involves taking into account previous and related research carried out in discovery and inquiry science, cognitive processing and thinking, and dialogue.

Ways must be found to evaluate whether or not "understanding through an act of conscious participation" is taking place during instruction. One of the best measures of understanding is whether or not the students can transfer and apply their learning to new situations and new problems (Minstrell, 1989). Any evaluation which is done in spontaneous conceptions research, then, should include problems which require transfer. Evaluation does not have to be limited to starting points and "products". It can also involve evaluating the actual process of learning itself as it is on-going. Methods of questioning and dialogue are one way to find out what changes are taking place in students' conceptions during instruction. Evaluation should also be directed toward other aspects of learning besides science content. One of the aims of teaching science for understanding is that students will not only acquire a better understanding of natural phenomena, but will also acquire a better understanding of the nature of science itself. Participation in science results in students learning more about scientific theories, scientific method, the development of scientific ideas, and so on.

When designing science instruction which differs from traditional, formal instruction, classroom realities must be kept in mind. That is, instruction designed in light of children's spontaneous conceptions should be practical in terms of classroom realities and should not place unrealistic and excessive demands on the classroom teacher and the students. Classroom realities include time pressure, social factors in classroom, teacher beliefs and knowledge, current teaching demands, curricula, textbooks, availability of materials, acceptable evaluation, and overall bureaucratic requirements. Ways in which these realities specifically affect instruction are class periods for instruction operate within certain time limits; classrooms usually contain up to thirty-five students; teachers may have philosophies of teaching which are not in line with suggested instruction; teacher knowledge may be inadequate for suggested instruction; content of the lessons may not fit with curriculum demands; textbooks may be misleading or contain actual errors; materials for experimental work may be lacking; evaluation may need to be summative and quantitative; and the school may already be committed to a particular model or method of teaching which is not in line with what is being attempted. Instruction which is designed solely for the purposes of research, then, may not work in the actual classroom because of the nature of classrooms and schools. At the same time, a research study may be designed in a particular way in order to explore the effects of an approach to instruction, but then may be later adapted specifically for classroom purposes.

For example, individual interviews may be used in a research study to discover students' spontaneous conceptions, whereas in the actual classroom, a combination of paper and pencil pre-evaluations and a knowledge of the history of science in a particular domain, may fulfil the same purposes. Also, optimistically, a new approach to instruction may assist in altering some aspects of the classroom status quo which are in conflict with it. In other words, classroom practice may have to accommodate the new method of teaching.

A general outline of how students might be moved from their spontaneous conceptions toward more scientific conceptions can be brought together from the work of a number of researchers. This approach to instruction can be summed up briefly as: focus, challenge, apply (Driver and Erickson, 1983). More specifically, the general approach involves diagnosing spontaneous conceptions; making the students aware of their spontaneous conceptions; having the students articulate their spontaneous conceptions; having the students compare their spontaneous conceptions with those of others; bringing about cognitive conflict by having the students empirically test their ideas so as to find examples and counter-examples; assisting the students in achieving a new understanding in light of their findings; contrasting the new and old conceptions; allowing students to test the applicability of their new ideas in new situations; and clarifying student's conceptions in light of their new understanding (Za'Rour, 1976; Nussbaum and Novak, 1976; Clement, 1979; Erickson, 1980; Osborne and Gilbert, 1980; Champagne, Klopfer, and Anderson, 1980; Nussbaum and Novick, 1981; Caramazza, McCloskey, and Green, 1981; Posner et al, 1982; Krupa, Selman, Jacquette, 1982; Clement, 1982; McCloskey, Washburn, and Felch, 1983; Eaton, Anderson, and Smith, 1983; Hewson and Hewson, 1983; Driver and Erickson, 1983; Ault, 1984; Ault, Novak, and Gowin, 1984; Driver, Guesne, and Tiberghien, 1985; Hashweh, 1986; Shymansky and Kyle, 1988).

A number of commonalities are also found among the same researchers as to how each aspect of the above process might be accomplished. Diagnosis of spontaneous conceptions can be done both by [illegible]earchers and teachers, with the aid of the history of science, through individual Piagetian clinical interviews, picture tests, think-alouds, and through written evaluative tests and inventories which can be administered to a group. Making students aware of their spontaneous conceptions can be initiated by the diagnosis and can be further developed through questioning. Nussbaum and Novick (1981) also suggest using an "exposing event", an event specifically designed to lead students to think about their ideas. Students can be encouraged to articulate their own conceptions individually through writing and diagrams. Individual written accounts, for example, in journals, ensure that no one is overlooked and also provide a record for both student and teacher. Students can compare their ideas with fellow students through dialogue, discussion, and debate, either in small groups or in a class discussion. Empirical tests can be devised by the students, with teacher help, and with the help of the history of science. Here there may be a place for computer simulations (DiSessa, 1982). Socratic dialogue, discussion, and questioning can be used to lead students toward a new understanding and to help them contrast their old conceptions with their new ones. Encouragement, discussion, time, opportunity, accessibility of materials, and linking to everyday life will help students apply and consolidate their new learning. Evaluation of what kind of learning is taking place should be carried out so as to focus on understanding rather than memorization. Two possible approaches are asking students to explain their understanding to other students and having students apply their learning to new and unfamiliar situations. It is instructive to note that several researchers warn that reconceptualization may take a long time and thus cannot be expected to occur "overnight" (Driver, Guesne, and Tiberghien, 1985).

A few further general principles applicable to the entire instructional process can be noted. First, throughout the entire process, the role of the teacher is extremely important because, while experienced scientists may become aware of, question, test, and draw conclusions from their conceptions on their own, students will have difficulty doing so because they differ from scientists in a number of important ways. These differences include age, intellectual capacity, repertoire of past experiences in scientific study, immediately relevant knowledge, and knowledge in other fields which might provide analogies and metaphors (Nussbaum and Novick, 1981). Second, if conceptual change instruction is to have a chance of success, students must feel secure in the knowledge that being wrong is all right, that is, the inquiry must be conducted in an atmosphere that encourages risk-taking, that declares that mistakes are okay (Fisher and Lipson, 1986). Third, the acquisition of a better understanding may not correspond with having the "right answer". Along with the attitude of the teacher and the nature of instruction, the history of science may be of direct help here. If children are aware that their spontaneous conceptions have parallels with ideas once held by great scientists and thinkers of the past, they may be less likely to feel that their ideas are silly or stupid, and thus will be less likely to develop a negative attitude toward a learning process which leads them to alter their ideas in light of new learning (Prather, 1985). Finally, it should be noted that during instruction, the students are participating with the teacher in scientific research in a manner similar to practising scientists, that is, by making hypotheses based on their spontaneous conceptions, testing them, and drawing conclusions from them. Thus, they are also becoming familiar with the nature of science, not by having it described to them but by "doing" it and by interacting with the teacher who is serving as a model. The teacher can model, for example, by encouraging hypothesizing, testing, belief consistency, consistency between theory and evidence, pursuit of simplicity, scepticism toward excessive ad hocness in theories, and a critical appraisal of whether results are in reasonable agreement with theory (Posner, 1982). In this manner, the approach to instruction is not only "about science", it is also scientific.

In Chapter Three, a small pilot study involving two children is described. The pilot study was based on the ideas drawn from reviewing the literature

CHAPTER THREE

PILOT STUDY

PURPOSE

The purpose of the pilot study was to attempt to use the notion of spontaneous conceptions in science as a basis for teaching the two primary school children the scientific concept of the finite divisibility of matter. Specifically, the approach to instruction was to first determine the children's spontaneous conceptions of the divisibility of matter, to have them focus on their conceptions, to present them with an event which contradicted their initial conceptions, and then to bring them to a more scientific understanding. A further purpose of the pilot study was to see if the children's spontaneous conceptions of the nature of matter showed any parallels with historical ideas concerning the nature of matter.

SUBJECTS

Two subjects were used in the study. They were selected for convenience, being children of the researcher. Stuart is seven years old and is in Grade Two. Ellen is in Grade Three. They are judged to be bright from report card marks, teacher comments, standardized tests, and selection for enrichment programs. Ellen and Stuart's parents are professionals with university education. The subjects were tested together in their home environment. All proceedings were audiotaped, and results transcribed directly from the tapes.

PROCEDURE

The science concept chosen to be taught was:

Matter is discontinuously made up of invisible molecules, each of which exhibit the properties of that matter.

This concept was chosen for three reasons: (a) it is a key concept in physics and chemistry, (b) it is not a concept which can be derived from observation and "commonsense" but must be deduced through thinking,and, (c) the historical development of this concept in science is clearly recorded.

HISTORICAL DEVELOPMENT OF CONCEPT

Briefly, the historical development of the concept is as follows (Rutherford, Holton, Watson, 1975):

"Earlier Greek philosophers thought that all the different things in the world were made out of a single basic substance (ibid p. 4).

"According to another view, that of Empedocles around 450 B.C., there were four basic types of matter--earth, air, fire, water. All material things were made out of them (ibid p. 4).

"The first atomic theory of matter was introduced by the Greek philosopher Leucippus, born about 500 B.C., and his pupil Democritus. Material things consisted of very small indivisible particles (ibid p. 4).

"The atomic theory was severely criticized by Aristotle. He argued that matter is continuous and infinitely divisible so that there can be no atoms (ibid p. 5).

"During the first ten years of the nineteenth century, the English chemist John Dalton introduced a modified form of the old Greek atomic theory (ibid p. 8)... The atomic theory of John Dalton appeared in his treatise, *A New*

System of Chemical Philosophy, published in two parts, in 1808 and 1810. The main postulates of his theory were (l) Matter consists of indivisible atoms. (2) Matter though divisible in an extreme degree, is nevertheless not infinitely divisible. That is, there must be some point beyond which we cannot go in the division of matter (ibid p. 11)...Dalton's interpretation of the experimental facts of chemical combination made possible several important conclusions...(3) Chemical combination is the union of atoms of different elements into molecules of compounds (ibid p. 14).

"Nineteenth century chemistry and physics converged, at the beginning of the twentieth century, on the problem of atomic structure. It became clear that the uncuttable, infinitely hard atom was too simple a model; the atom itself is made up of smaller particles" (ibid p. 116).

DESIGN OF INSTRUCTION

The following instructional program was planned as a means of determining their spontaneous conceptions, then moving them from their spontaneous conceptions to more scientific conceptions:

1. The subjects were asked to examine a glass of water, to taste it, and to describe it. The water was divided up into smaller and smaller containers. Each time the subjects were asked to determine if it was "still water". Eventually, drops of water were placed on the table and divided up again and again. The subjects were then asked how small the amount of water could become and still be water. A microscope was displayed and the subjects were asked if the water could be divided into water parts so small that they could only be seen through a microscope.

2. The subjects were encouraged to describe their spontaneous conceptions about the continuity or discontinuity of matter verbally and to draw pictures illustrating how long they thought the water could be divided.
3. The subjects were assisted by the experimenter in stating their spontaneous conceptions as clearly and succinctly as possible, so that they could become aware of all the implications of their spontaneous conceptions.
4. The subjects confronted each other with the pros and cons of their individual conceptions, in order to increase both their understanding of their own conceptions and of any differences in their two conceptions. This was done verbally and with reference to their illustrations.
5. The subjects were told that an attempt would be made by the researcher to divide up water even further. To do this it was necessary to use a special tool, since conventional tools would be limited by their physical nature. The special tool was electricity. It was noted that lightning was electricity and that it could "break things up", for example, trees. The subjects then watched the progress of the electrolysis of water (Volta first conducted this experiment in 1800 when water was still regarded as an element rather than a compound). Their attention was drawn to the gases in the test tubes and they were asked where they might have come from. The gases were tested with a burning splint (oxygen--increased glow, and hydrogen--squeaky pop) to demonstrate that they were not air. It was concluded that they could have only "come from the water".

6. Since it was clear that the electricity had broken the water into smaller bits which were not water, the researcher proceeded to guide the subjects in a search for a conception which would explain the observed phenomena. The researcher used a method of representing the new conception in a manner which was at the level of the children (Case, unpublished). This involved an analogy with compound words. A graphic was displayed with the word "football", in smaller and smaller type. Further down the page in the graphic, "football" was broken into its constituent words, "foot" and "ball". It was noted that when football was broken into its constituent words, each constituent took on a new meaning. The analogy was drawn with water by using a second graphic where water was printed smaller and smaller, then broken into hydrogen and oxygen. The children were asked to describe how oxygen and hydrogen differed from water, that is, they were both gases, were invisible, and did not extinguish the glowing splint. The word "compound" was introduced as a descriptor of a substance made up of other different substances, and the word "molecule" was introduced as a descriptor of the smallest amount of water which was still water. The principle of discontinuity of matter was equated to other examples where parts may differ from a whole, such as the human body.
7. The students were encouraged to state and explain the new conception in a comprehensive manner. This included applying the idea to another compound, i.e., salt, and to generalizing the concept of discontinuity of matter to apply to all compounds.
8. The students were asked to explain the concept of molecule the following day to see if the new conception was still retained.

RESULTS

The subjects understood that water could be broken down into smaller and smaller quantities and still remain water. At the same time, they had difficulty in quantifying that amount, for example, Ellen at first stated that the smallest amount possible would be "half what you have there", while Stuart said it would be "one-quarter of what you have there". The researcher then demonstrated that even smaller amounts were possible by dividing up drops using a pin. At this point, it seemed the children still needed a physical representation in order to grasp the size of "the smallest particle". However, they agreed that the smallest amount could be so small that a microscope would be needed to see it.

When asked again how long the water could be divided, after the microscope was introduced, Stuart stated, "Until there was nothing left". Ellen characterized the amount as "the tiniest drop you could ever make", as big as "a germ in your body". She then agreed that this could be further divided into "half a germ", and that this would "still be water". When asked again how long the water could be divided, she stated: "Forever and ever and ever and ever". At this point, both children, seemed to be articulating an Aristotelian notion of the continuity of matter.

When asked to draw her notion of "a tiny bit of water", Ellen drew a series of smaller and smaller circles. Stuart seemed a little puzzled as to what to do and didn't draw anything. The request was changed to ask the subjects to draw a picture of a big amount of water which showed how it was made of tiny bits of water. Stuart drew a more or less round circle with "little tiny veins" and star-like blobs inside. He said his representation was round because it was seen through a microscope, and that the "veins" and star-like blobs made up the "water particles" which made up the water. He thought there might be about "a few million" particles making up his amount of water. Ellen drew a similar representation. Her shape was more irregular and the inside of it was filled with short scribbly lines, and dots made by banging the point of her pencil on the paper. She described her particles as "like little tiny spices". She thought there might be "about a thousand" particles making up her amount of water. When reminded that she had stated that the water could be divided forever and asked how many particles this would make, she replied "eight lying on its side", in other words, infinity. Stuart nodded agreement to this. Again, both seemed to be articulating the Aristotelian notion of continuity of matter.

The children agreed that there would be great difficulty in physically dividing the water beyond a certain point Stuart said, "It would get too small". Ellen nodded agreement. To introduce the demonstration, the researcher drew an analogy between electricity and lightning, and asked if lightning could split things. Ellen stated that lightning could split trees in half. The researcher then stated that he would use electricity to further "split up" the water. At this point, the electrolysis apparatus was brought out, with the process already occurring. (It was thought that because electrolysis of water takes about an hour, continuity between the first part of the presentation and the second would have been lost if the process had been started from scratch. At the end of the demonstration, the whole experiment was restarted and the subjects viewed it periodically over its duration, about an hour and a half.)

The researcher asked the children where the electricity came from in the electrolysis set-up. Both replied, "The battery". The battery had "battery" written on it. When asked if they could say where else batteries were used to produce electricity, both declared, "In a flashlight". When their attention was drawn to the test tubes, now partly full of oxygen and hydrogen respectively, they declared that the water was coming out and that the tubes were filling up with "air". Then they noticed that the bubbles were coming from "the water or the wire". It was then shown via a sideline demonstration that air could not enter the tube when the tube was filled up with and immersed in water. Ellen then concluded that "something was going in", while Stuart suggested that "the air's pushing the water out". The subjects were then shown an "empty" test tube and asked asked what was in it. Both subjects replied, "air". Next, the subjects were shown via a sideline demonstration that when a glowing wooden splint was pushed into the air-filled tube, nothing untoward happened, in particular, there were "no noises.". This was to highlight the next demonstration. It involved removing the tube containing hydrogen from the electrolysis set-up and pushing a lighted match into it, causing a loud and startling "pop". Stuart concluded that there was not air in the tube just tested "because if there would have been air in it, it would have popped in the glass jar." Ellen added that what was in the test tube must have something to do with "the electricity bolt".

The subjects were then shown the graphic of the word "football" in smaller and smaller letters, finally breaking into "foot" and "ball". They concluded "it divides into parts", the parts being "foot" and "ball". They agreed that "foot' and "ball" on their own differed from the compound word football". A foot was not a football and a ball could be any kind of ball, not just a football. An analogy was then drawn between "football" as a compound word, a term they were familiar with, and "water" as a compound, using the second graphic which portrayed the word "water" in smaller and smaller print, followed by its division into "hydrogen" and "oxygen". The subjects noted that "Water, water, water got smaller and smaller" (Ellen), "then it divided into hydrogen and oxygen" (Stuart). The researcher asked, "What did the electricity do to the water?" and Ellen replied, "Divided it into hydrogen and oxygen". The researcher asked: "Are hydrogen and oxygen the same as water?' Both subjects answered, "No". The researcher stated: "When we started our work together, you both said that water could be divided "forever" and still be water. Do you still think so?" Ellen replied: "Now I think that after it got really small, it would got (sic) into hydrogen and oxygen." After the meaning of the word "compound" was clarified, an analogy was drawn to point out that water was also a compound, but of a different kind. Stuart stated: "Water is a compound because it's made up of two different things". The word "molecule" was then introduced as "the smallest amount of water you could have that would still be water". Further, the generalization was made that the smallest amount of other compounds were also called "molecules", and that "molecule" was thus a general term used to describe the smallest amount of any compound. The subjects then concluded that a compound could be divided up "until it splits into two different things" (Ellen). The researcher also reiterated that a molecule was too small to be seen, even by a microscope. In conclusion, it was pointed out by the researcher that most "things" we come into contact with in our daily lives are compounds. Examples such as salt and sugar were mentioned.

DISCUSSION

At the beginning of the task, it seemed that the subjects held an Aristotelian view of matter, that is, that matter was continuous. Although they at first expressed the idea that the division of matter would stop at some point, it would appear that their main reason for stating this was their inability to think in terms of very small quantities, as evidenced by their use of the words "thousand" and "million" interchangeably. Their idea of discontinuity was due to their inability to conceive of matter as being physically rather than theoretically divisible beyond a certain point. Certainly, they did not at any time express the view that divided beyond a certain point water would become "something else". The metaphor of a "germ" proposed by Ellen, as the epitome of something too small for the naked eye, seemed to be extremely useful to both of the subjects in finally clarifying their representation of an extremely small quantity, which led to their finally stating the Aristotelian view that water could be divided "forever".

The use of the "exposing event", that is, the division of water into smaller and smaller containers, seemed to serve its purpose. That is, it did lead to the subjects actually articulating their conception of matter as being continuous. The comparison of the two drawings lead to a description by each child of his or her particular drawing, rather than a "comparison" of likenesses and differences. However, this could be attributed to the fact that both drawings expressed fairly similar views, and that there were only two drawings up for discussion. In classroom instruction, one would hope that a larger sample would result in more variety in viewpoints and a more extended, lively, and useful discussion, which would lead to further clarification of student views.

The use of the "discrepant event", the electrolysis of water, also seemed to serve its purpose. The subjects were able to conclude that the electricity was breaking down the water, that the test tubes were filling up with something, that the "something" was connected with the fact that bubbles were coming from the terminals, and that the "something" could not be air. The "pop" from igniting the hydrogen served to highlight the difference between air and whatever was in the test tube very dramatically. This led to the subjects' readiness to accept the idea that the tubes contained something totally new, that is, hydrogen and oxygen, and that these gases resulted from the breaking down of water by electrolysis. It should be noted that the selection of the discrepant event was partly inspired by the history of science. Dalton's first inkling for his atomic theory lay in his discovery that elements also combined in the same proportions when forming compounds. Thus history can be a source of discrepant events, as well as a reference for a general outline of conceptual development.

Both subjects had been exposed to compound words in their schoolwork prior to the research, as evidenced by worksheets they had brought home. This was the reason it was used as an analogy for chemical compounds. But the subjects did experience difficulty in making the necessary jump from words to chemicals. At first, they were confused because although "water" was not a compound word, it was still a chemical compound. That is, water is not a word made up of two other words, but it is a compound made up of two other elements. It is clear that an analogical move from one concept to another can be quite confusing for children and must be made with extreme care and clarity.

At the end of the task, the children were able to articulate their conclusions concerning the discontinuity of matter. This would point to the success of the instructional method in creating a state of cognitive dissonance, leading to a new understanding. However, it should be noted that the subjects experienced difficulty in generalizing from the case of water to other compounds. For example, at the beginning, they seemed to feel that the word "molecule" only applied to water, that is, that it was a word specific to water. This points to the need for any generalizing to be brought about not just from one case but after a number of related examples have been clearly set out to illustrate the same concept.

In terms of instruction, it is clear that it is quite difficult to isolate a single concept for teaching purposes. First, it was necessary to present the idea of molecules and to omit mention of atoms for purposes of clarity of presentation. This could be handled in actual teaching in a classroom by presenting the concept of the discontinuity of atoms in a subsequent lesson in a manner similar to that used for molecule. Second, the need perceived by the researcher to use words such as compound, molecule, hydrogen, and oxygen from the vocabulary of science, three of which would be new to the average seven or eight-year-old, points to a possible difficulty in the area of language. Certainly, exposure to new vocabulary should be carefully handled to avoid confusion. Third, presenting the concept of molecule required also mentioning compounds. The two concepts are closely linked and it is impossible to present one without the other and still make sense. Perhaps, then, instead of having students come to understand their conceptions singly, it might be necessary to have them bring to light a whole group of interrelated concepts. These concepts could be "mapped" (Clement, 1979) as a starting point for a comprehensive program of instruction. Thus, the program of instruction could be redesigned in light of not one but of a whole interlocked group of conceptions held by the students (Eaton, Anderson, and Smith, 1984).

Discovery or inquiry science has used "discrepant events" for some time. However, the idea of "exposing events" is comparatively new. It should be emphasized that the task above posits that in science inquiry, before a discrepant event can have an effect and create cognitive dissonance, the student must become aware of the conception with which it is dissonant with, that is, with her spontaneous conception. This is accomplished through the exposing event. Further, it should be noted that, as practised, discovery science often varies according to the amount of teacher input. The extremes go from completely unguided "messing around" to totally teacher-directed activities. Although scientists may be able to make new scientific discoveries by "messing around" without guidance, it is much more difficult for students to do so because different conclusions can be induced from the same data and students differ from scientists in a number of important ways (Nussbaum and Novick, 1982). It is reasonable to conclude that the teacher must play a role in guiding inquiry, just as the researcher did in the task described in this account. This role could be generally characterized as a flexible balance between guiding and challenging.

Children's spontaneous conceptions come from their attempts to explain their experiences with the natural world. Most often, these spontaneous conceptions do not concur with present-day scientific thinking. This is not surprising. It would be unrealistic to expect children to come to clear, modern-day scientific conclusions on their own. Teaching, then, is important in helping children come to understand present-day scientific conceptions. This conclusion may sound obvious but it has two important implications. First, just allowing children to "mess around" in science in a strict Piagetian sense is probably not enough. Second, if we take the view that there is something wrong with trying to assist children in moving from their spontaneous conceptions toward more scientific conceptions, we will probably delay their acquisition of scientific conceptions.

In Chapter Four, the methodology of the main study is described. The experience of the pilot study was useful in helping to design the study.

CHAPTER 4

METHODOLOGY

PURPOSE

The study's purpose was to test an approach to science instruction based on the spontaneous conceptions of the students involved. A main assumption of the approach is that students' spontaneous conceptions affect the manner in which they become involved with the content and process of a science unit. In particular, it assumes if the students' spontaneous conceptions are not taken into account, they could actually provide a barrier to learning by causing students to interpret new concepts in terms of their spontaneous conceptions. Students would tend to assimilate new learning into their spontaneous conceptions, which would remain essentially unaltered, rather than accommodate new learning by altering their concepts. However, if instruction began from the spontaneous conceptions of the students, then improved understanding would take place. This understanding could involve both the content and processes of science. It was assumed that the spontaneous conceptions of the students would interact with the scientific conceptions of the unit. The spontaneous conceptions would provide a starting point for learning in ways in which the scientific conceptions would develop and systematise the spontaneous conceptions.

A further research purpose was to investigate whether or not the history of science could provide any assistance to the teacher in science teaching. If parallels with students' spontaneous conceptions could be found in the history of science, then the history of science could be helpful to teachers in a number of important ways. First, the history of science could help predict what spontaneous conceptions students may hold. The history of science could provide a heuristic device by which teachers could shortcut the involved and time-consuming process of finding out what spontaneous conceptions students were likely to bring to the science class. Second, the history of science could suggest to teachers and students how scientists historically arrived at their conceptions, that is, it could provide a source both for critical discussion and for possible student experiments. Third, the history of science could demonstrate how earlier conceptions in science developed into later conceptions, that is, the manner in which scientific ideas have changed over time. Fourth, the history of science could assist in maintaining the intellectual confidence of students by showing both that the development of scientific ideas throughout human history is a closer and closer approximation of objective truth, although with twists and turns, and that the spontaneous conceptions now held by students were once held by scientists of the past.

CONTEXT

The study was carried out in a Grade Six science class in an elementary school in a large western Canadian city. The school was located in a middle class neighbourhood. The class consisted of thirty students, fifteen boys and fifteen girls, of varying abilities. The class was taught science throughout the year by their regular classroom teacher. During the 4 week study, about three hours per week, one hour per day, was devoted to science classes. The science content for the study was the content of a unit previously selected by the classroom teacher. It was the Elementary Science Study (ESS) unit, *Optics*. This unit emphasizes hands on "discovery" as the approach to learning science, and centres around a kit of student materials for various experimental investigations of optical phenomena. A teacher guide is provided which outlines the possible student investigations. There is also a supplementary school board guide which outlines some further investigations. The teacher had taught this unit to other classes. In the past he had usually only completed part of the unit activities because of time limitations.

The researcher had ten years experience teaching science at the elemntary level. He prepared for the content of the unit by going over four kinds of materials. First, he looked at the optics unit the teacher would be using (Lange, 1971; Kay et al., 1972). He also looked at three other popular elementary science units on the topic of light to see what content was covered and what approaches were used (Blecha, et al., 1977; Rockcastle et al., 1972; Carin and Sund, 1975). Second, the researcher read books and articles on light and colour (Rossotti, 1983; Jollands, 1984; Wyszecki, 1988) to improve his understanding of the science content. Special attention was paid to recent developments in colour research (Montgomery, 1988; Nathans, 1989). Third, the researcher read in the history of science to become familiar with the historical development of ideas about seeing and colour (Newton, 1931; Said, 1969; Ronchi, 1970; Macadam, 1970; Lindberg, 1976, 1983; Wasserman, 1978). Finally, the researcher read research studies on childrens' spontaneous conceptions of light and colour to become familiar with previous research in this area (Finegold, 1974, 1976; Stead and Osborne, 1980; Anderson and Smith, 1983; Anderson, 1986: Zylbersztajn and Watts, 1983; Andersson, 1983; Driver et al, 1985; Eaton et al, 1986; Goldberg and McDermott, 1986; Shapiro, 1987).

In carrying out the study, an attempt was made to stay in conditions as close to classroom conditions as possible. The ultimate aim of research in education is to improve classroom practice. It is, therefore, important for researchers to make such application as easy as possible, that is, to make their research as practical as possible in terms of classroom conditions. The research was developed and done in collaboration with the classroom teacher. The teacher selected the science content. A general plan for instruction was discussed with the teacher, then modifications were made in light of the researcher-teacher discussion. For example, the teacher wished to insert a vocabulary lesson among the researcher-directed lessons and this was done. Also, the classroom teacher wanted to use small groups at certain points in his instruction, so this was incorporated into the study. The research was done with the sort of class a regular classroom teacher would have rather than with a small group in a laboratory setting. Conditions in classrooms differ radically from small group laboratory conditions. The research was completed during regular science instruction times. This meant different starting times and also, at times, gaps of two or three days between lessons. Again, this arrangement approximates the realities of classroom life. To maintain the collaborative relationship between researcher and teacher, ongoing discussions continued during the research. The researcher also assisted the teacher in other areas, for example, by obtaining a laser for a student demonstration not related to the research. After the researcher completed his study, the classroom teacher continued to work with the class on the optics unit in order to carry out his own plans for regular classwork.

INTERVENTION AND INQUIRY

The instructional intervention focussed on the students' understanding of two conceptions related to light and colour: (1) How do people see objects? (2) Why do objects appear coloured when we look at them? These two conceptions were selected as basic and important to an understanding of light and seeing (Anderson, 1986). The instructional starting point was provided by the responses to the pre-evaluation and interviews conducted in order to discover students' spontaneous conceptions about both concepts. There were three consecutive instructional sessions for each concept. In the first session, the main student conceptions, derived from the pre-instructional responses, were outlined by the researcher and then discussed by the students both in small groups and in whole class discussions. Students were asked to try to determine a way in which they could show by argument and/or experiment that the conception which they held at the end of the class was the best explanation for the phenomenon under consideration. In the second lesson, students presented their arguments and experiments to their own group and later discussed them in the whole class setting. In the third lesson, the researcher presented the scientific theory which was held at least partially by some students. This was followed by a whole class discussion. In all sessions, the researcher tried to emphasize that the most important thing to take place in the small groups and in the whole classroom was serious investigation and discussion of ideas with the aim of understanding natural phenomena. It was stated that such serious investigation and discussion could even preclude a majority of students from finding out the "correct answer" at that time. The need for critical discussion was particularly emphasized for the lessons in which the researcher presented the current scientific theory. Students were asked to examine the presentation critically, to aim for understanding rather than memorization, and to raise questions which might bear on the topic. After each session, the students were encouraged to make an entry in their science response journal. In the journals they were to express their ideas about the two conceptions mentioned above, that is, (1) How do people see objects?, and, (2) Why do objects appear coloured when we look at them?

After the students had selected from the conceptions put forward by the class, they were encouraged to investigate further following a pattern of inquiry. This pattern of inquiry into the chosen conceptions, applied to an example relevant to the study, could be characterized as having the following parts (Finegold, 1976): 1) A guiding conception: White light is pure and colourless 2) A problem for enquiry: Is white light colourless or made up of all colours? 3) Data: Observation of the effect of a prism on a beam of white light. 4) Interpretation of data: The colours must come from the white light. 5) Knowledge claim: White light is made up of all colours. After an opportunity to inquire into one or more of the possible conceptions, the students were asked to consider the scientific conception as a possible explanation for the phenomenon under consideration. The purpose of the inquiry was not necessarily for the students to end up accepting the scientific conception as the best explanation for the phenomenon under investigation. Rather, the purpose was for the students to deepen their understanding of natural phenomena and of science through participation in the inquiry.

TIMETABLE

The research was conducted in blocks of approximately one hour over a period of one month. As noted above there were sometimes gaps between sessions. Specific sessions are described below.

1. Two consultations were held with the classroom teacher. The first consultation was held to explain the nature of the study, to find out what the teacher's plans for the science unit were, to discuss the selection of subjects for interviews, and, in general, to decide what preparations had to be made by researcher and teacher before the study commenced. The second consultation was held to discuss the

researcher's more detailed plans, drawn up in light of the first discussions. An outline of these plans was presented to the teacher for consideration. Times for the research lessons were determined in accordance with the teacher's schedule.

2. The researcher administered the pre-evaluation (see Appendix A). The pre-evaluation was a three-page paper and pencil "test", with questions derived from work done by Anderson. Anderson has conducted extensive investigation into how students think about light (Anderson, 1986; Anderson and Smith, 1983; 1986). The purpose of the evaluation was to discover students' spontaneous conceptions about light and colour, particularly in relation to, (1) How people see objects, and, (2) Why objects appear coloured when we see them.
3. The researcher interviewed five students. They were selected for in-depth interviews in order to gain more insight into their spontaneous conceptions. They were selected as representative of a variety of abilities as judged from the pre-test, as including a nearly equal number of boys and girls, and as compatible (as judged by the classroom teacher) as a working group. The selection was not random. The individual interviews were conducted at the back of the classroom around mini-demonstrations using the same questions asked on the pretest. For example, a flashlight beam was shone through a green transparency and students were asked why they observed the light on the other side of the transparency to be green.
4. A vocabulary lesson was taught by classroom teacher. The classroom teacher presented the students with terms related to the optics unit, for example, "optics", "reflection", and "wave theory". The students were asked to hypothesize the terms' meanings. Selected students

looked up the terms in reference books and the appropriate definitions were agreed upon. The researcher observed this lesson but did not participate.

5. Researcher presents students' models of seeing (see Appendix D). The purpose was to allow students to clarify their own views on how we see and to test their views against those of others (Nussbaum and Novick, 1982). The pre-evaluation revealed that the students in the class as a whole basically held to four different theories of how we see objects. These were labelled by the researcher as the illumination theory, the visual rays theory, the combination theory, and the reflection theory. Those who held to the illumination theory drew rays from the sun to the tree only. Those who supported the visual rays theory drew a set of rays from the sun to the tree and another ray or rays from the eyes of the observer to the tree. Those who leaned to the combination theory drew rays from the sun to the tree, from the tree to the observer, and from the observer back to the tree. Those who decided on the reflection theory drew rays from the sun to the tree and then from the tree to the observer (see Appendix A).

The researcher presented these four theories of seeing to the whole class, visually and orally (see Appendix D). He asked the students to discuss the four theories in small groups in order to determine the one which best describes how we see. In their groups the students were told to express their own ideas and listen to the ideas of others. The students were to support their ideas by arguing for them or by describing an experiment or actual instance which might support their viewpoint. It was emphasized that the students did not have to reach a consensus and could conclude by disagreeing with each other.

At the end of the small group discussion, each member of the group would try to come up with a way to test their theory experimentally. After the small groups met, the whole class was called together again for a brief discussion.

6. The researcher was available for consultation with students concerning materials, a suggestion made by the classroom teacher. The researcher was available in the classroom for several hours so that students could consult with him about how they planned to go about verifying their views on how we see. They were also able at the same time to ask the researcher to obtain materials which might not be available in the *Optics* kits or otherwise in the school.
7. The researcher organized student investigations of models of seeing (see Appendix D). The students were divided into small groups in order to defend their choice of a seeing model by argument and/or experiment, first in their small groups, and then in the whole class. During the group work, the researcher interacted with the interview group.
8. The researcher presented the reflection theory of seeing (see Appendix D). The researcher presented evidence in support of this scientific theory to the students. Students were encouraged to look at this model critically, rather than to accept it as the "correct answer".
9. The researcher presented students' models of seeing colour (see Appendix D) in the same manner as for the models of seeing. The responses to the pre-evaluations revealed that students held two theories of why objects appear coloured. The first theory, supported by the vast majority of students, was that colour is an innate property of objects. This theory could be summed up as red objects appear red

because they are red. A related idea is that when coloured (monochromatic) light illuminates a coloured object, the eye perceives a colour which is a mixture of the pigment and of the light. For example, if a red light illuminates a green object, the resulting colour perceived will be a mixture of red and green. Another variation of this second idea is that the light colour will dominate the "object colour", that is, that any object of any colour, seen in, for example, red light, will appear red. The second theory held by the students was that objects appear coloured because the pigments in them absorb certain colours (wavelengths) of light and reflect other colours (wavelengths), that is, objects reflect the colours which our eyes perceive.

In addition to the two theories of colour, the researcher presented some of the implicit assumptions about the nature of light which lie behind each of the two theories. Specifically, three additional related ideas were discussed which followed from the main premise of each theory. These ideas were: 1) White light is either colourless and pure or is made up of all colours; 2) White light either illuminates objects or certain colours of white light are absorbed by objects and certain other colours of white light are reflected; and, 3) We see colour either because we "look at" coloured objects or special cells in our eyes are sensitive to certain reflected colours of light. These additional ideas were presented to make it easier for the students to devise experiments to support one theory or the other. The researcher suggested that if the students could not think of an experiment which supported their overall theory of how we see colours, they might still be able to think of an experiment related to one or more of the additional implicit assumptions. After the introduction of the two theories and the discussion of the assumptions, the class broke into the same small groups.

10. The researcher organized student investigations of models of seeing colour (see Appendix D). This followed the same process as for the models of seeing. This time the experiments were conducted in an area made as dark as possible to eliminate all sources of light except the light boxes from the *Optics* kit. Each group was supplied with coloured squares of paper, coloured filters, masks for the light boxes, mirrors, and prisms. Each group also had a flashlight to use when needed. It should be noted that investigations into seeing colour lend themselves much more readily to experimentation than do investigations into how people see.
11. The researcher presented the reflection theory of seeing colour (see Appendix D). This was done following the process described in Step 8 above.
12. The researcher administered the post-evaluations to class. The post-evaluation was exactly the same as the pre-evaluation (see Appendix A). These were given in order to determine how students' ideas might have changed over the period of the inquiry.
13. The researcher re-interviewed the five students to see how their ideas might have changed over the period of the inquiry.

DATA SOURCES

There were a number of sources. Notes were made by the researcher immediately before and after each session. These notes sketched out plans for lessons and also recorded events not taped. There were paper and pencil pre-evaluations on optics. Five students were interviewed and the interviews recorded on audiotape. Audio tapes were also made, and later transcribed, of all class sessions. In small group situations, whole class taping was stopped and taping was continued with the interview group. If a whole class discussion followed small group work, the whole class was again taped. The response journals kept by the students over the period of the research were collected at the end of the research. At the end of the study, students completed the same evaluation as before the research. The five students interviewed before the research were reinterviewed and the interviews taped. All transcription of audiotapes was done by the researcher.

As far as the researcher can determine, there has been little use made of response journals in science education. While the use of science notebooks by students is a common occurrence at all grade levels, generally these notebooks have been concerned with lab write-ups, diagrams and graphs, and specialized vocabulary. Response journals, on the other hand, are more diary-like in style, are expressive of what students think rather than what teachers think, and give information about students' conceptual development. Journal entries are completed at the end of the class and provide a chance for students to reflect on what they have experienced during the lesson. This reflection can take the form of words, pictures, and/or questions (Kydd, Jones, and McAlister, 1988). For the purposes of this study, students were encouraged to make daily journal entries which tracked the progress of their understanding of the two questions already outlined, (1) How do people see objects?, and, (2) Why do objects appear coloured when we look at them? The instructions for the journals, first presented at the end of the pre-evaluation, asked the students to write, draw diagrams, or answer in a way which best expressed what they thought. There were no length requirements for entries. The journals were collected at the end of the study and used as one data source.

DATA ANALYSIS

Data analysis may be summarized under the following six questions. The data sources provided some answers to the questions:

1. What spontaneous conceptions did the students bring to the instruction? The data sources were the first interviews, the pre-evaluations, and the first journal entries.
2. Do the children's spontaneous conceptions have parallels with the history of science? The spontaneous conceptions were examined in light of the history of science (see Appendix C).
3. What happens to children's spontaneous conceptions during the instructional intervention? The case studies of three students from the interview group were analyzed (see below for a discussion of the selection and use of the case studies). The daily entries in the response journals of all students were another source. The whole class discussions were a third source.
4. What conceptions did the students have at the end of the instructional intervention? The post-interviews, the post-evaluations, and the final journal entries are data sources.
5. How closely do these final conceptions resemble scientific conceptions? The conceptions outlined in the post-evaluations were compared with scientific conceptions.
6. How firmly do the students hold to their new conceptions, that is, do the new conceptions tend more to rote memorization or to deeper understanding?

In looking at these questions, it should be noted that Questions 3 and 6 are the most difficult. The instruction was designed specifically to take into account children's spontaneous conceptions in science. The reason for taking these into account was the hope that doing so would allow children to reach a better understanding of natural phenomena. As noted above, the purpose of the instruction was not necessarily to have every child articulate a scientific conception at the end of the study. The strategic, long-term purpose of science instruction should be a scientific understanding but the articulation of a scientific conception after a particular series of lessons or activities or interventions does not necessarily indicate such an understanding has been reached. This study attempted not only to look at the changes in the students' conceptions following the instructional intervention but also the process of that intervention and the interaction of the students with, and during, that process. In general, it was thought that the changes in students' conceptions, the processes of that change, and the depth of the conceptions acquired by the students, are all important evidence as to the effects of the instructional intervention. All three aspects must be considered if a comprehensive data analysis is to be carried out.

In the data analysis, the results of the overall group and of three students from the interview group were examined in detail. This use of two types of analytical approaches was on the grounds that the two approaches are complementary, that is, quantitative analysis provides precision while qualitative analysis provides scope (Roberts, 1982). The evaluations, the journals, and the whole class discussions provided means of looking at the overall group. The ideas expressed on the evaluations both before and after the intervention were categorized according to their commonalities and analyzed. Individual summaries were made of the ideas expressed in the journals of all thirty students, with special attention to how these ideas changed or did not change. The taped whole class discussions provided a means of looking at the ideas of some of the students during the instructional intervention. Analysis of the discussions centred around those questions which the students raised repeatedly and/or discussed at length. It was assumed that if these particular questions occupied a great deal of the students' time, the discussion of them must be important to the students' understanding of the natural phenomena under investigation.

The case studies of three members of the interview group provided the second approach to analyzing the data. Data for the case studies came from the evaluations, the interviews, and the whole class and small group discussions. Case study students were selected from the interview group because the largest amount of data was available on the interview group students. Three students only were selected in order to limit the number of case studies. The three students picked were chosen because they made the biggest contributions to the small group discussions and because they were easy to distinguish by the sound of their voices. Two boys and one girl were selected to try to represent both sexes. It was thought that the case study method provided the best means of tracing in detail how individual spontaneous conceptions changed over the time of the instructional intervention. By looking at the specific ideas of selected individual students over time, we gain insight into why the ideas of the students changed or didn't change, that is, of what specific factors might be affecting their thinking during instruction. Looking closely at individual children also fits most closely with classroom reality in that teachers are mainly concerned with discovering what individual students have learned. Finally, the case study method was selected as a preliminary investigation which would bring out more specific themes which could become topics for future research.

The research study conducted is a preliminary investigation. The sample was not randomly selected. The study uses design and analysis methods appropriate to the study's purpose. It does not "take sides" regarding the superiority of one methodology over another. It is not a complete and definitive investigation into the questions which it takes up. There is, however, an assumption underlying the research that some approaches to science instruction are better than others and that the aim of research into science instruction should be to discover and develop such methods.

CHAPTER 5
DATA ANALYSIS

Part One: Students' Conceptions Before Intervention

DATA SOURCES

The purpose of the pre-evaluations, the pre-interviews, and the first journal entries was to discover students' spontaneous conceptions about light and colour. The pre-interviews, which were administered only to five students, asked the same questions as the pre-evaluations, but were accompanied by mini-demonstrations. The pre-evaluations consisted of ten questions which related to seeing, light, and colour (see Appendix A). The journal entries were to focus on two general questions: "How do people see objects?" and, "Why do objects appear coloured when we look at them?" The journal entries do not provide much information beyond the pre-evaluations because entries were brief and almost always duplicated the pre-evaluation responses. Therefore, the pre-evaluations and the pre-interviews are used as the main data source for the students' spontaneous conceptions. Twenty-six pre-evaluations were collected and examined* .

IDEAS OF THE WHOLE CLASS

How Does Light Help Us to See Objects?

In response to this pre-evaluation question, the students gave answers falling into the two general categories of "illumination" and "reflection". The essence of the illumination idea is that light illuminates objects and that this is the sole role of light in seeing. In almost all of the cases where the illumination idea was expressed, only light was mentioned and any reference to how we see was omitted. The implication of these answers is that light and seeing are two separate phenomena, that is, light illuminates the object, then we "see it". The illumination idea was expressed by the students in terms such as, "You can't see without light", "You can't see in the dark", "Light lights up the object", "Light amplifies colour, texture, and shape", "Light shines on the object", "Light brightens up the object", and "Light illuminates the object." About two-thirds of the students gave "illumination" responses.

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* The names of all of the students have been changed for anonymity.

The essence of the reflection idea is that light reflects off the object. That is, after light hits the object, it bounces and continues its journey. Some students thought that this reflection was directed to the observer's eyes, while others simply stated that the light just "reflects" or "reflects off". The reflection idea was expressed in terms such as, "Light shines on the object and goes into your eyes", "Light makes up the object and reflects off", "Light reflects off the object and your eyes read the reflection", "Light bounces off objects to our eyes", "Light reflects off the object", and, "The light hits the object and then your eyes". About one-third of the students gave "reflection" responses.

Some students, about one-third of the total, made specific mention of the eyes in their responses. In conjunction with the "illumination" idea, the eye was characterized as "seeing" the illuminated object. There was no direct connection made between the light illuminating the object and what the eye sees, that is, illumination and seeing were treated as two "separate" operations. This conception was expressed in terms such as, "Light shines on the object. Our eyes and brain do the rest", "Light brightens up the object and makes us focus on it", "Light shines on the object. Our eyes see the object." The eye was also specifically mentioned in conjunction with reflection. Here the eye was described as a receptor of reflected light from the object. This was stated in terms such as, "Light shines on the object and your eyes read the reflection", "Light shines on the object and goes into your eyes", "Light bounces off objects to our eyes", and, "The light hits the object and then your eyes."

One student gave a "visual rays" interpretation of seeing, that is, he specifically mentioned something traveling from the eye to the object: "Light shines on the object, goes into your eyes, and back to the object." No students made any specific reference to light images or to images falling on the retina of the eye. Their explanations were limited to the general role of light and, sometimes, to the general function of the eye, that is, the eye as an organ of sight without any specific physiology. If the evidence of the scientific conception of seeing is construed as a statement that light reflects off the object to the observer's eyes, even though no image is mentioned, only about four students held this as an initial conception.

Draw Arrows to Show How Light From the Sun Helps the Girl See the Tree

The students were presented with a diagram of the sun, a tree, and a girl, and were asked to draw arrows to show how the sunlight helps the girl to see the tree (see Appendix A). The students' responses were categorized by the researcher into four conceptions, called the illumination theory, the visual rays theory, the two way theory, and the reflection theory (see Appendix B, version 1).

For the illumination theory, the sun's rays were drawn as falling on the tree or on the tree and the girl. These were the only rays or lines drawn. Seven of the students depicted the illumination theory, of which four showed the rays falling on the tree and the girl and three showed the rays falling only on the tree.

For the visual rays theory, the sun's rays were drawn illuminating one or both of the girl and the tree, and some type of "line of sight" was drawn from the eye of the girl to the tree. This "line of sight" was represented either by an arrow pointing from the girl's eye to the tree or by a dotted line connecting the eye and the tree. Ten students depicted the "visual rays" theory. All drew in the visual ray. Of the ten, five showed the sun's ray(s) falling only on the tree, two showed the sun's ray(s) falling only on the girl, and three showed the sun's ray(s) falling on both the tree and the girl.

For the two way theory, the sun's rays were drawn falling on one or both of the tree and the girl, and a ray or line of sight was drawn which traveled both from the tree to the girl and from the girl to the tree. The connection from the tree to the girl was shown as a reflection of a sun's ray from the tree to the girl. The connection from the girl to the tree was either a further reflection of the ray from the tree to the girl, or was a distinct and separate "line of sight". Four students depicted some version of the two way theory on their diagram.

For the reflection theory, a ray(s) was drawn traveling from the sun to the tree and then reflecting to the observer's eye. No other rays of any kind were drawn. Five students depicted the reflection theory. Of these, all but one drew only a single ray from the sun to the tree to the eye of the observer. This one student drew a series of lines from top to bottom of the tree, all of which reflected near to or to the observer's eye. These last five students might be thought of as holding a scientific conception of how we see objects.

Why Can't John See the Penny in the Bucket?

The students gave three types of answer to this question. These could be grouped into "line of sight", "could but can't", and "reflection". Two students gave no answer at all, one by inserting "I don't know" and the other by leaving the question blank.

The students who gave the line of sight response suggested that the sides of the bucket prevent John from seeing the penny by blocking his "line of sight". They made a specific reference to either an obstruction by part of the bucket or else to the penny's location in the bucket, and, except in one case, a specific reference to John's inability to "see" the penny. The line of sight idea was expressed in terms such as, "The side of the bucket is blocking John's line of sight", "The edge closest to him blocks his view of the penny", "John cannot see the penny because it is in the bottom corner of the bucket", and "The penny is in the bottom corner of the bucket and the glass stops a bit of his view". Eleven students gave a "line of sight" response.

The "could but can't" response suggests that John actually can see the penny in the bucket but some factor other than the side of the bucket is preventing him from seeing it. The students who gave this response seemed to reinterpret the given problem diagram in one of two ways. The first reinterpretation assumed that the side of the bucket is not between John and the penny at all, that is, a straight line can be drawn connecting John's eye with the penny. The second reinterpretation assumed that the sides of the bucket are made of some transparent material, such as glass, and so, once again, there is no obstruction between John's eye and the penny. The students who reinterpreted the problem came up with factors other than the side of the bucket as preventing John from seeing the penny. The three specific factors they mentioned were glare, shade or shadow, and lack of contrast. These factors were incorporated into explanations such as, "The light is reflecting onto the penny so the light is very bright and would hurt his eyes", "The glare is on the side of the glass", "The light bulb reflects on the glass like a mirror and it gets too bright to see", "The light is reflecting off the glass so the penny is hard to see", "The shadow makes it so he can not see it", and "The light makes the penny look like the bottom of the bucket". Ten students reinterpreted the problem and gave a "could but can't" response.

One of the two "reflection" responses mentioned reflection but in a way that made it unclear whether the student grasped the idea of seeing by reflection. The exact response was, "Light just shines down into the container and then the light stays there and moves around inside the glass container". Possibly this student is trying to state that the light reflecting off the penny does not reach John's eye, but his thinking is not clear from his statement. The other "reflection" response was very clearly stated: "The light reflected from the penny is blocked by the bucket." This one student seems to have a scientific conception of how we see and has applied it to John's situation.

Why Can John See the Penny After the Bucket is Filled With Water?

The responses to this question fit into five categories, called, respectively, "relocation by reflection", "elimination", "magnification", "redirection", and "seeing by reflection". One student responded, "I don't know". In relocation by reflection, the basic premise was that the water had "reflected" the penny to a new location where John can see it. That is, the side or edge of the bucket was still between the penny and John, but was not between the "reflection" of the penny and John. This relocation was expressed in terms such as, "The penny gives a reflection", "The penny's reflection in the water", and "The penny reflects onto the water". In this explanation, instead of seeing the actual penny, then, John sees its reflection at a new location. This seeing, however, is not connected to reflected light. Ten students thought the penny was reflected to a new location where John could see it.

The elimination idea was presented by those students who had previously suggested that John actually "could" see the penny but there was some other factor such as glare, shadow, or lack of contrast. Following from their initial premise, these students stated that the water had eliminated what they saw as the source of the problem. This elimination idea was stated in terms such as, "The water is clear and the penny shows through", "The water blocks light", "The water is a light colour and absorbs the light", and "The water reflects the light to the penny so he can see it". Nine students used this type of explanation.

The basis of the magnification idea was that John could see the penny because somehow the water made the penny look larger or closer. In other words, the water acted like a lens. This idea was expressed in terms such as, "The water has altered the image so it now looks closer. Now it's an illusion," "The water has appeared to enlarge the penny", and "The water makes things bigger than usual". Three students suggested this type of solution to the problem.

One student made specific reference to a redirection of John's line of sight by the water. This was stated exactly as: "The water reflects the light going into the bucket therefore his sight is distracted and sent in a different direction. In this case it is sent to the bottom of the bucket." This explanation is a direct application of the visual rays theory.

One student gave an ambiguous response which made reference to reflection of light. He stated: "The light shines on the water and then reflects off it so he can see it." This is ambiguous because it could mean that the light illuminates the water and thus the object, or it could mean that light reflects off the object to the observer's eyes. One student made a clear reference to reflected light: "John can see the penny because the light reflected off the penny reflects through the water to his eyes." This student also drew arrows on his diagram which showed the light being "bent" or refracted towards John's eyes as it left the water. This last student seems to be the only one who has a scientific conception of both reflection and refraction and thus of why John can now see the penny.

What Happens to the Light From the Flashlight After It Hits the Objects?

The four objects were a mirror, a piece of translucent glass, a piece of clear glass, and a piece of white wood. For the mirror, all but one of the twenty-six students drew arrows which showed that the light reflected back off the mirror. Of these, about fifteen drew their arrows in a manner which appeared to represent an attempt to show the reflected rays rebounding at the same angle as the incident rays. The one student who did not show the light reflecting, drew a "star" on the back of the mirror. This may have represented his attempt to show what an observer would see "inside the mirror". In any case, the class as a whole clearly understood that the mirror reflects light.

For the translucent glass, eleven students thought that the light would stay on, or stay in, or stop on or be absorbed by the object. In other words, the journey of the light would somehow end at the translucent glass. These students made no mention of reflection at all. Seven students thought that the light would go straight through the frosted glass. In other words, they gave the same answer for the frosted glass as they did for the clear glass. (Note: a verbal explanation of "translucent" was given and an example shown to the class, before the students answered this question.) None of these students made any mention of reflection. One student thought that some of the light would "stay on" and some would go through. Seven students thought that some of the light would go straight through the translucent glass and that some would be reflected off. However, only one of these seven students drew a diagram which seemed to show the light scattering rather than reflecting off coherently. The latter represents the scientific explanation of what would happen to the light, that is, the light would both reflect and scatter, and go through and scatter. Only one of the students, then, seemed to understand the scientific conception of scattering.

Twenty-two of the twenty-six students used arrows to show the light travelling straight through the clear glass and beyond it. This is a scientific understanding of this phenomenon. Two of the remaining students drew "blobs"-on the other side of the glass, as if the light went through and then stopped somewhere just on the other side. The other two students used arrows to show the light travelling through the clear glass, but also drew arrows to show that some light reflected off the glass. One of these students wrote, "Most of the light will go through but very little will be reflected". The other wrote, "Most of the light would go through the glass but some would be reflected." These latter two students may have a deeper understanding than those who only drew the light going right through, since they may be illustrating the idea that, although the majority of light travels coherently through clear glass, the glass would be visible only if at least some light was reflected off it. As a whole, then, the class understood that light passes coherently through clear glass.

For the white wood, thirteen of the students depicted the light as stopping at the wood. This was described in terms such as, "It just hits the wood", "(Light) would shine and show on wood", and, "The wood will be lighted up". These students, then, believed that the light would not reflect off the wood. Five students thought that the wood would both absorb light and reflect light. This was stated in terms such as, "Some light would be absorbed but most of the light would be reflected", "The light will go into the wood but would not go all the way through and then it would reflect off", "The light will absorb white light but reflect other colours", "The light would go but only some would not come out because white takes in one colour and gets rid of the rest". The other eight students depicted the light reflecting off the wood. One of these eight seemed unsure about the reflection, stating, "The light would bounce off a little bit". Three of these eight drew diagrams which, when compared with their mirror diagrams, seemed to show the light scattering rather than being reflected coherently, although none used the word "scattering". Finally, one of the eight stated that "The wood would reflect the light but the light would not be visible." Eight of the students, then, presented the basic scientific conception that light would reflect off the white wood. Of these eight, four seemed to be demonstrating a deeper understanding by trying to show that the light reflected from the white wood in a different manner than from the mirror, that is, that light scattered from the white wood.

Why Does a Black Object Look Darker Than a Grey Object?

Eleven students gave an answer to this question which simply restated the question. They stated that black looks darker than grey because black is darker than grey. Three of these students expanded on their answers, stating respectively, "Black is not a colour and grey is", "Black consists of every colour except grey", and, "Because grey is made of black and white mixed but black is just black". All eleven of these students see colour simply as an innate property of the object. They see no connection between light and colour.

Fifteen students stated their answers in terms of one or both of absorption and reflection. They stated that black absorbs more light than grey and/or that grey reflects more light than black. Three of these students used the word "attracts" instead of "absorbs", while one student used the phrase "takes in". These students understand that colour involves an interaction between the object and light, whereby light is absorbed and/or reflected by the object to varying degrees. This is the scientific explanation of why black looks darker than gray. Just over half the students, then, held a scientific conception of this phenomenon.

What Does the Coloured Glass Do to the White Light Shone Through It?

As this question was a multiple choice question, the answers can be simply categorized by which of the four choices was selected. One student selected three of the four answers, one of which contradicted the other two. Ten of the students selected (a) The glass adds red colour to the light. These students, then, assumed that white light is pure and colourless and that colour is something which the red glass added to the white light. Five of the students selected (d) The glass turns the white light into red light. Again, these students assumed that white light is pure and colourless and that colour is something which the red glass added to the white light. Two of the students selected both (a) and (d). Four of the students selected (b) The glass lets all the light through but stops all the colours except red. This answer also assumes that light and colour are separate phenomena. Four of the students selected (c) The glass lets red light through but stops all the other kinds of light. This answer assumes that white light is made up of all colours, and that the red glass stops all the colours other than red. That is, the filter performs a "subtractive" rather than an "additive" function. (C), then, is the scientific conception of what happens to the white light at the red filter. Only four students chose this conception as the best explanation.

What Colour Will the Green Plant Appear in Green Light? Why?

Ten students suggested the plant would appear a colour other than green. Seven of these thought that this new colour would be a result of the green of the light and/or the plant mixing with the red of the pot. The result of this combination was variously stated as red-green, brown, black, blue, and yellow. Two students thought the plant would appear red because the red of the red pot would be dominant over the green of the plant. One student thought the green of the light would combine with the green of the pot to make blue. All of the above students explained the colour which appears as the result of either pigment alone or as a combination of the colour of light and the colour of pigment. These students are all assuming that colour is an innate property of objects, and that light is an external factor which "adds in".

Sixteen of the students stated that the plant would appear green or some shade of green. Of these sixteen, thirteen either did not explain their reasoning but simply made a descriptive statement along the lines of, "There is green light and/or a green plant", or else explained that there was an addition of the green of the light to the green of the plant, that is, green plus green equals green. These students, then, also thought of the "final" colour as being a combination of the pigment of the plant and the colour of the light. They see light and colour as separate, that is, colour is an innate property of objects and light is an external factor which illuminates the coloured object. The other three of these sixteen made some reference to reflection. This was in terms such as, "The same colour of light bounces off to make the whole room green", "The green light will shine on the green plant giving off green light", and "The light reflects green". These three students are applying the concept of reflection to colour, and seem to have a more scientific understanding of why the plant appears green in green light.

What Colour Will the Red Pot Appear in Green Light? Why?

Seven students thought the pot would appear either green or red. Four of these students said that the pot would remain red or appear "normal". One of the two students who explained his reasoning on this stated the pot would be, "Red because it always was red". The other explained that it would be red because "Red is stronger than green." Two students thought the pot would appear green. One stated this was because the light would dominate. The other stated that this was because the green light plus the green of the plant would be stronger than the red of the pot. Finally, one student thought the pot would appear either red or green, depending on which of the two colours was stronger. All these students see colour as innate in objects. To them, light and colour do not interact at all but are totally separate phenomena.

The other nineteen students thought that the green of the light and the red of the pot would combine to make a new colour. The majority of these students predicted that this new colour would be either brown (6), purple (5), or greenish-red (4). Other colours mentioned as the new colour were black, yellow, and "whatever colour green and red make". These students conceive of light and colour as interacting, but see this as a process of mixing rather than reflection and absorption. None of the twenty-six students, then, applied the scientific principles of absorption and reflection to this problem, not even those who had done so when tackling previous problems of light and colour.

Why Does a Blue Book Appear Blue?

As this question was a multiple choice question, the answers can be simply categorized by which of the four choices was selected. Fifteen students selected (a) The light helps our eyes to see the blue colour of the book. These students conceive of colour as an innate property of objects. The colour is "there" and we "see it" when it is illuminated by light. One student selected (b) The book absorbs blue light and reflects other colours. This student is applying the principles of absorption and reflection to colour but is confused as to the scientific meaning of each principle. Ten students selected (c) The book reflects blue light and absorbs other colours. These students are applying the principles of absorption and reflection to colour. The answer they have selected is the scientific conception of this phenomenon.

Why Are There Only Three Primary Colours of Light And Not Some Other Number?

Eight students did not answer this question. Four students gave miscellaneous answers: "They are used most", "They are used more", "Because the other colours make black", and "Because things reflected will almost always be white, black or yellow. The colours black and white reflect things to other colours." The other fourteen students answered that there are only three primary colours because all the other colours can be made from these three primary colours. This answer is a definition of primary colours but is not an explanation, that is, it does not tell why there are only three primary colours and not some other number. A scientific explanation would connect the number of primary colours with the three types of colour-sensitive cones in the eyes. That is, the number of primary colours corresponds to the number of cones. None of the students, then, gave a scientific explanation.

What Are the Three Primary Colours of Light?

Eight students gave answers other than red, yellow, and blue. These eight answers were "red, yellow, white", "black and I don't know the other two" (note: "white" crossed out), "green, red, white", "black, white, and grey", "red, orange, and yellow", "white, blue, and yellow', "white, black, and yellow", and "I don't know." The only common denominators in this group seem to be the inclusion of "white" by five of the students and "black" by three of the students. Also, one student wrote "red" and "yellow" but excluded "blue".

The other eighteen students wrote that the three primary colours of light were red, yellow, and blue. These are the three primary colours of pigments, but they are not the three primary colours of light. The three primary colours of light are red, blue, and green.

INDIVIDUAL CASE STUDIES

Shawn

Shawn was a member of the interview group and, thus, of the small group on which the researcher focussed when the students engaged in groupwork. When his small group convened, Shawn was always the first to put forth his views and he generally did so at length. He usually tried to arrive at an overall understanding of a phenomenon, rather than just picking up on a partial or side issue. For example, he would state, "That's my theory", after a long explanation. Shawn seemed to think as he talked, that is, he often changed his line of thought in mid-sentence. Basically, he contributed more than his share of words to the small group. At times he interrupted other students to present his own ideas. In the small group, Shawn most often interacted with Paul; they would consider each others' ideas and dialogue about them. In the whole class discussions, Shawn made no contributions although he sat quietly and appeared attentive. He presented all his comments in the small group setting.

Shawn's Ideas Before Instructional Intervention

The sources for Shawn's ideas before the instructional intervention are his pre-evaluation, his taped interview with the researcher, and the first entry in his response journal.

Where Does the Light in This Classroom Come From?

In response to the first interview question, Shawn is clear on the sources of light for the classroom we are in. He points to the lights and the window. He also agrees that light will come into the room from the other adjoining classrooms.

How Does Light Help Us See Objects?

Shawn's pre-evaluation and response journal give the same information on his conception of how we see objects. In both he writes: "The light shines on the object or light bulb and then the light goes into your eyes and back at the object." On his pre-evaluation, in his diagram of how the girl sees the tree, Shawn draws in arrows from the sun to the tree, from the sun to the girl, and back and forth from the tree to the girl (Diagram 1). Shawn is presenting a "two-way" theory of seeing, where the light is reflected from the object to the observer and then is "sent back" to the object as some type of "visual ray".

When Shawn is asked in the interview how we see a chair in the room, he explains.

> Shawn: The light would shine down on me and the chair and then the light would reflect off my eyes and then you would see the chair.

Here he shows that he understands that light plays a role in seeing and also that seeing involves reflection. At this point in the interview, it is not clear if he understands light as reflecting from the chair to his eyes or if he understands light as just illuminating the chair, so a further question is asked.

> Researcher: Does the light reflect off the chair?
>
> Shawn: If the object was like glass then the light would probably go through it and then just straight through like that. If it was on

> something like a chair and the chair was wood, it would probably just bounce off the opposite way.

Shawn, then, seems to grasp the concept of reflection of light from objects, but not that this reflection is directly responsible for seeing the object. Instead, it is more likely that Shawn feels that both the object and the observer must be illuminated before the observer can see the object. To Shawn, the light which comes to the observer is not the image of the object, but is both direct and reflected light, light which then travels from the observer to the object, thus allowing her to see the tree. Shawn understands that light is necessary for seeing, and, more importantly, that light reflects, an important step in understanding how we see objects. However, at this point he does not understand that an image of the object is reflected to our eyes. To Shawn, "seeing" is still something which ultimately "goes" from the eyes to the object.

Why Can't John See the Penny in the Bucket?

Shawn's response to this question supports the latter interpretation. On the pre-evaluation, Shawn comments that the observer cannot see the penny because "the light shines down into the container and then the light stays there and moves around inside the glass container". On the pre-evaluation diagram, Shawn adds ray lines which show the light shining straight down into the bucket, then bouncing back and forth from side to side, but always staying inside the bucket (Diagram 2). In the interview, Shawn explains.

> Shawn: There's no light there. My head's blocking the light maybe.
>
> Researcher: What about some of this other light?
>
> Shawn: When light is there then the light will just stay right there.
>
> Researcher: What do you mean by right there? Inside?

> Shawn: Yes. Then it will just bounce off and I can't see the light because there's a shadow there.

Again, Shawn's explanation points to an essentially "illumination" view of seeing. That is, the penny cannot be seen because there is no illumination which allows the observer to see. In other words, the penny is "in the dark" in terms of the observer. Hence Shawn's comment about a shadow. It is interesting to note that Shawn makes no mention of the sides of the container blocking the "line of sight" or the "view" of the observer. Again, it seems he has a vague notion of the importance of reflection to seeing, but cannot connect this with an image of the object.

Why Can John See the Penny After the Bucket is Filled With Water?

Shawn has difficulty explaining why adding the water to the container makes the penny visible to the observer. This is not surprising since this phenomenon involves a grasp of both reflection and refraction. On his pre-evaluation, Shawn presents his idea of reflection from the water more clearly: "The light shines on the water and then reflects off so he can see it". Shawn's addition to the pre-evaluation diagram supplements this explanation. Shawn draws the rays from the light bulb above the container bouncing off the surface of the water and contacting the observer's eye (Diagram 3). Unfortunately there are no directional arrows on the rays. In his interview, Shawn makes a different suggestion.

> Shawn: Maybe the light shines down right there and since there's water maybe the light goes right through it and then back out or something.

Here he falls back on the idea of reflection again.

> Researcher: If we only had air in there, would the light have gone right through?
>
> Shawn: Yes, because you can't see air.

Shawn's Ideas Before Instructional Intervention

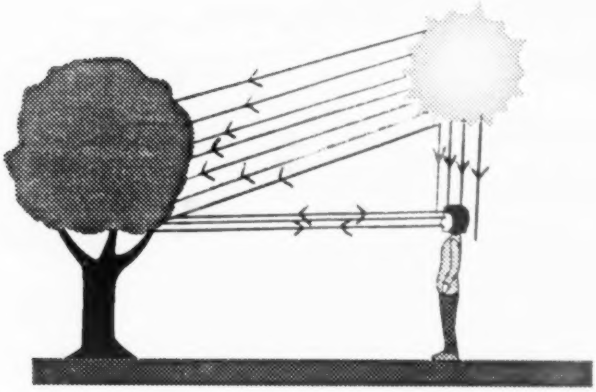

Diagram 1: *Draw arrows to show how light from the sun helps the girl to see objects.*

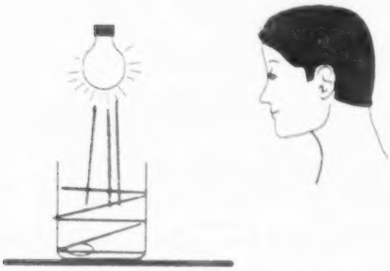

Diagram 2: *Why can't John see the penny in the bucket?*

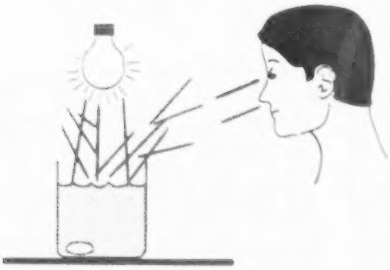

Diagram 3: *Why can John see the penny after the bucket is filled with water?*

> Researcher: How would water be different from air as far as light goes?
>
> Shawn: Well air is lighter than water, so maybe the light shone down on that and when the air was there maybe the light just stayed in there and then back out or something.

Shawn is quite confused. He attributes the different behaviours of light in the different media to the fact that water is heavier than air and that somehow the light acts differently in each one. Here might be seen the germ of an idea that light behaves differently in media of different densities, an idea basic to understanding the nature of refraction. Shawn sees light as acting differently in relation to water than air because water presents a reflective surface. Again, Shawn is connecting the idea of reflected light with seeing. However, he does not conceive of the reflected light coming from the object to the eye. Instead, the reflected light is bouncing from the surface of the water to the eye and makes seeing the penny possible through illumination.

What Happens to Light From the Flashlight After it Hits the Objects?

Shawn has quite a clear idea of how light behaves when it contacts various objects. He writes and says that light bounces off a mirror. On the pre-evaluation mirror diagram he draws two reflected rays as parallel and at approximately the same angle as the two incident rays. In the pre-evaluation, Shawn states that light "spreads out" when it hits a piece of frosted glass. Shawn's addition to this diagram shows reflected rays of light travelling both along the surface of the frosted glass and also bouncing backward. Here may be seen some understanding of scattering from non-smooth surfaces. In the interview, where the flashlight and frosted glass are actually used in a mini-demonstration, Shawn suggests that the light goes straight through the frosted glass. This may be due to his observation of the physical evidence of light on the other side of the frosted glass. Possibly he was not clear on exactly what was meant by a translucent surface although an explanation was given by the researcher during the pre-evaluation. In the pre-evaluation, Shawn obviously thought of frosted glass as an opaque substance, whereas in the interview demonstration, he showed a different understanding because he could see some of the light going right through the frosted surface. Shawn is clear that light travels "right through" transparent glass. Shawn is also clear that light bounces off a white opaque surface.

> Shawn: Light hits it and goes that way and that way. If you shone a light through (glass) the light would pass right through it and then if you shone the light on a piece of wood, then there's no clear stuff and so it would go some other way.

Shawn's diagram on his pre-evaluation shows the light bouncing off the wood in exactly the same manner as off the mirror. Perhaps, then, he feels that light bounces off all opaque objects the same way and really does not have any idea about how light scatters from non-smooth surfaces.

Why Does a Black Object Looks Darker Than a Gray Object?

Shawn basically sees colour as an innate property of the object. Shawn's response on his pre-evaluation is that "the light will reflect on black and not on grey." The fact that he wrote in the word "not" originally before "reflect", then crossed it out, then wrote it in again, then crossed it out again, shows his hesitancy on this matter. However, here again he brings up reflection as a property of light. When interviewed as to why the black paper appears darker than the grey paper, Shawn answers in terms of the light illuminating the papers.

> Shawn: The light shines on grey, the light makes it look lighter maybe, and when it shines on black it's like a shadow and so it makes it look darker.

Researcher: Can you explain it in terms of the colour, in terms of the gray or the black?

Shawn: The light looks whiter here on the grey and it looks darker here because the piece of paper is already black and so it shines down and it stays black because it's already black. So it's sort of like a shadow on a piece of black paper.

As well as his essentially circular explanation, that is, that black looks black because it is black, Shawn also seems to feel that the illuminating light is affected by the lightness or darkness of the surface it illuminates, that is, "when it shines on black it's like a shadow and so it makes it look darker", and "the light looks whiter on the grey".

What Does the Coloured Glass Do to the White Light Shone Through It?

On his pre-evaluation, Shawn selects as his answer that it is because the glass adds red colour to the light. He gives a similar verbal response to the related interview question.

Researcher: Where does this colouring come from?

Shawn: From the green stuff right here because when the light passes through it's gotta be like green.

It is clear that Shawn holds the implicit assumption that white light is pure and colourless and that colour is something which is added to white light. For Shawn, there is no colour in white light.

What Colour Will the Green Plant Appear in Green Light? Why?

When asked on the pre-evaluation, Shawn suggests that the explanation here lies in a combination of colours of the two phenomena: "Green because there is one green light in a dark room and there is a plant." In other words, green plus green equals green. The only colour present in any form is green, therefore the answer is obviously "green".

What Colour Will the Red Pot Appear in Green Light? Why?

Shawn again reveals his view that colour is an innate property of objects, independent of light. He answers that the colour of the light will not affect the colour of the red, that is, "It will appear normal." In other words, the red pot will appear the same colour as it does in white light.

Why Does a Blue Book Appear Blue?

It is interesting to note the difference among Shawn's explanations for why an object appears coloured. On the pre-evaluation, Shawn selects from the alternatives given the correct scientific explanation, "The book reflects blue light and absorbs other colours". In his journal, he states almost the reverse of this idea, attributing colour to the eyes of the observer: "There are special colours in our eyes and if we see something green the colour in my eyes reflect off and onto the object." Finally, in the interview, he goes back to the idea that colour is an innate property and white light illuminates the object so we can see it:

> Researcher: Why does it (the book) appear to you as blue?
>
> Shawn: Because the light makes me see it blue.
>
> Researcher: In what way does the light make you see it blue?
>
> Shawn: It shines light on the book and my eyes and the light...I don't know.
>
> Researcher: Is what you're saying, some of the light shines on the book and some of the light shines on your eyes? Is that what you're saying?
>
> Shawn: Yeah, then I can see the book because the light...I don't know.
>
> Researcher: So the light lights it up?
>
> Shawn: Yeah.

From three sources, then, we have three different explanations. These are, objects appear coloured because they reflect a particular colour of light; colour is a function of the observer's eye; and colour is an innate property of objects which is visible in light. Shawn is unable to express one clear conception of why objects appear coloured when we look at them.

Why Are There Only Three Primary Colours of Light? What Are They?

Finally, on his pre-evaluation, Shawn states that he does not know why there are only three primary colours of light. However, he guesses that the three primary colours are yellow, red, and blue. These are the three primary colours of pigments, not the three primary colours of light. It is quite possible Shawn has had experiences mixing paints and has learned that all other colours may be made from these three. He is assuming, then, that the situation regarding colours of light is analogous to the situation regarding colours of paint.

Paul

Paul was also a member of the interview and small group. He only contributed once to the whole class discussion and did not speak too often in the small group, spending more time listening to the others, especially Shawn. Paul was often asked by Shawn for confirmation of Shawn's ideas. However, Paul did not always agree with what Shawn said. Paul did not hesitate at times to admit that he "did not know" and that he could not explain certain phenomena. Paul sometimes inserted extremely perceptive comments into the ongoing dialogue, comments demonstrating that he was trying hard to make sense of what was under discussion. At times he expressed precise scientific ideas about optical phenomena even though scarcely participating in the discussion.

Paul's Ideas Before Intervention

The sources for Paul's ideas before intervention are taken both from his pre-evaluation, his taped interview with the researcher, and from the first entry in his response journal.

How Does Light Help Us to See Objects?

In his pre-evaluation, Paul explains that light helps us to see objects because "if we did not have light, why not just be blind? After all, you can't see anything without light." This is a straightforward illumination theory of seeing, that is, that light "brightens up" the object so that we can see it. In his diagram of the observer and the tree, Paul draws arrows only from the sun (Diagram 4). These arrows impinge on both the observer and the tree. Paul writes on his diagram that, "The sun hits all around the tree and around her." The diagram, then, affirms Paul's illumination view of how we see.

In the pre-interview, Paul notes that light in the room originates from the lightbulbs and the sun. He also comments that light is energy. He then explains how light helps us to see the chair in the room.

> Paul: Why it (light) reflects off the chair and it just makes it so you can see a bit better. Light comes down onto the chair and makes the colours spring out so you can see them.

Again, Paul presents his illumination theory. When the researcher asks about the role of his eyes, Paul replies, "I'm not sure. They play the watching part."

In his journal, Paul writes that how people see objects is that "They turn on the lights." This is similar to his pre-evaluation where he saw seeing merely as a function of whether the object was in the light or in the dark.

Why Can't John See the Penny in the Bucket?

Paul writes the following as his explanation of why the observer cannot see the penny in the bucket: "The glare is on the side of the glas" (sic). He then originally wrote "and is reflecting into his eyes from the water", but crossed this out and instead continues, "No, no, no. It is shining off the coin and the sides so he can't see." On the diagram, Paul draws a line straight down connecting the light bulb to the coin (Diagram 5). He also draws another line to a star-like shape against the side of the container closest to the observer and labels it, using a short arrow, as, "bright". This is the "glare". Finally, he draws an arrow from the far side of the container to the observer's eye. Paul's explanation, then, is that there is a glare in the eyes of the observer which prevents him from seeing the penny. Although the question clearly states throughout that the container is a bucket, Paul seems to have assumed that it is transparent glass.

In the pre-interview, where an actual opaque container is used, however, Paul's attention is drawn to the positioning of the side of the container.

> Researcher: What would your explanation be for why you can't see the penny now?
>
> Paul: Because this little part of the plastic is in the way.
>
> Researcher: What's it in the way of?
>
> Paul: The view of my eyes to see the penny.

This is a common-sense summary of the situation, that is, the side of the container is blocking Peter's "view".

Why Can John See the Penny After the Bucket is Filled With Water?

Paul's explanation in the pre-evaluation of how pouring in the water makes the penny visible is consistent with his notion of "glare". The penny

Paul's Ideas Before Instructional Intervention

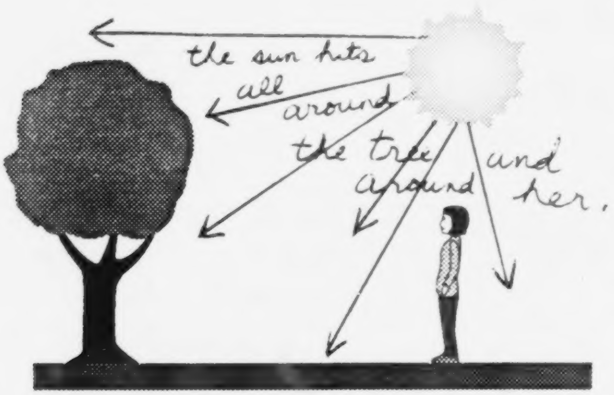
the sun hits
all
around
the tree
around
and
her.

Diagram 4: *Draw arrows to show how light from the sun helps the girl to see objects.*

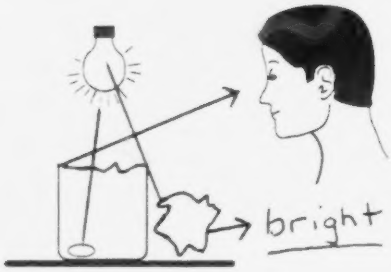

Diagram 5: *Why can't John see the penny in the bucket?*

(Paul did not complete the diagram *Why can John see the penny after the bucket is filled with water?)*

becomes visible because "He can see through the side because there isn't as much glare." Paul adds nothing to the diagram. According to Paul's previous statement, the observer cannot see the penny when there is no water, even though the container is transparent, because there is a glare off the penny and the glass. After the water supposedly eliminates this glare, the penny becomes visible once again. Because Paul has assumed the container is transparent, the significance of the positioning of the side of the container between the penny and the observer's eye is completely irrelevant to him, and so he looks for the source and solution of the problem in an entirely different place.

In the pre-interview, when the water is poured in, Paul tries to explain why he can now see the penny:

> Paul: The water goes to the side and it darkens the spot and so you can kind of see it, a little tint.
>
> Researcher: Anything else?
>
> Paul: Actually the water makes the plastic a bit lighter and the penny darker. The light shines at the water and then the water is up that high and the light goes off the penny and onto the wall so you can see it through, I guess. I'm not really sure on that question.

It is difficult to make sense of what Paul is saying but he does bring out the idea of distinguishing objects from each other by contrast of light and dark, that is, the contrast between the lightness of the plastic and the darkness of the penny makes the penny visible. His own conclusion, "I'm not really sure", probably sums up his thoughts best at this point.

What Happens to Light From the Flashlight After it Hits the Objects?

On his pre-evaluation Paul shows the light from the flashlight hitting each object with a kind of "splash". For the mirror he extends the pre-drawn arrows to the other side of the mirror and locates his starlike "splash" at the end of the extensions. He writes: "There would be a bright circle in the mirror." For the frosted glass, he places the splash on the same side as the flashlight, then draws four very faint lines going in different directions from the other side of the glass. He comments: "It hits and goes through in glares that can not be seen." For the clear glass he draws a splash on each side. He writes: "It goes right through with a bit of glare, not enough to hurt your eyes, though." Finally, for the white wood, instead of a splash he draws a small circle tangent to and placed more or less inside the sides of the mirror. He notes: "All you see is a white bloch (sic)--brighter than the wood." Although Paul realizes that the light goes through the clear glass and partially through the translucent glass, he never once mentions the phenomenon of reflection, even when discussing the mirror.

In the pre-interview, where the effect of each surface on the flashlight beam is actually demonstrated, Paul alters his responses slightly. He now decides that, when shone on the mirror, "the light reflects off it and comes back". When probed as to whether all the light reflects, he suggests that, "Some of it might stay in. Most of it comes back out." When the light is shone on the translucent object, "A bit of the light stays in it and most of the light goes past." When asked if any light reflects from it, he answers, "Yeah, a bit." For the clear plastic, "It goes right through", although, "Just a tiny little bit of it stays in it and goes back just a tad." By "goes back", Paul appears to mean "reflects". Finally, the light shone on the white wood "just turns into a white dot." No light goes through the wood and no light reflects off it. Paul is straightforwardly describing his observations in these accounts. For example, his statement that light "stays on" the white wood is a description of what he sees when the light is shone on the wood, that is, he sees a "blotch" of light "on the wood". His slight alterations to his views after being probed may represent changes in thinking or may show his knowledge of the "education game" where, if the teacher asks about something, the best response is to, at least partially, go along with it.

Why Does a Black Object Look Darker Than a Gray Object?

Paul gives a circular explanation of why a black object looks darker than a gray object "because it is a darker colour, I think". In other words, black is darker than gray because black is darker than gray. The assumption is that colour, at least black or gray, is an innate property of objects.

Paul starts off to give this same view in his interview.

> Paul: The grey is a lighter colour and you can see it better in the light. Actually the grey is a lighter colour than the black.
>
> Researcher: Could you say anything in terms of light?
>
> Paul: Black takes all the light in and grey collects it all so you can see it.

Here Paul is moving toward a more scientific explanation by mentioning "absorption", that is, "takes all the light in", and "reflection", that is, "collects it all so you can see it".

What Does the Coloured Glass Do to the White Light Shone Through it?

Paul selects as his explanation that "the glass turns the white light into red light". Paul's explanation in his pre-interview is the same.

> Paul: The white light goes through the green visor and picks up the green type colour of the visor and shines it on the piece of board, which is greenish.

In both instances Paul expresses the implicit view that white light is by nature colourless and, therefore, any colour in light must be an additive to it. For Paul, the source of the added colour can only be the filter through which the light passes.

What Colour Will the Green Plant Appear in Green Light? Why?

Paul feels that the green plant in the pot will be green in green light "because it is green". Green is green is green, that is, colour is an innate property of objects.

What Colour Will the Red Pot Appear in Green Light? Why?

Paul feels that "the red pot will be dark red because the green light makes it look darker". Again, colour, is an innate property of objects which may be darkened or lightened by coloured light but not essentially altered.

Why Does a Blue Book Appear Blue?

Paul confirms his view of colour as an innate property in responding to this pre-evaluation question. He selects as his answer, "the light helps our eyes to see the blue colour of the book." Colour, then, is innate and light illuminates the colour so we can see it. Paul's answer in the interview to the same question about a blue book reveals the same thinking: "Because the light shines on it and it's painted the colour blue so it looks blue, dark blue."

In his journal, Paul answers the question, "Why do objects appear coloured when we look at them", by writing, "because they have colour and the light shines on them." Again, this is consistent with his answers above, that is, it expresses an illumination theory of seeing and an innate theory of colour.

Why Are There Only Three Primary Colours of Light? What Are They?

Paul thinks that there are only three primary colours of light "because they all mix into three colours." Perhaps he means that various mixtures of the three primary colours create all the other colours. He is most likely transferring his knowledge of pigments to light. Finally, Paul guesses that the three primary colours of light are "black" and "I don't know the other two". At first he wrote "white" but then crossed it out.

In his journal, Paul states that people see objects when "they turn on the lights". This view is consistent with the "illumination" theory which he outlined at the start of his pre-evaluation and pre-interview. His view on why objects appear coloured when we look at them is also consistent with his other ideas: "Because they have colour and the light shines on them." Again, for Paul, colour is an innate property of objects, and is illuminated by the light which shines on the objects.

Cari

Cari was also a member of the interview group and the small group. She spoke up fairly often in the small group and also made a few contributions during the whole class discussion. In the small group she interacted mainly with Zelda. Sometimes she would make comments to Zelda but then would not repeat them for the rest of the group, even when asked. Several times, Cari and Zelda found themselves united and opposed in their views to Shawn and Paul. For example, Cari and Zelda argued that a certain object looked dark-green, while Paul and Shawn argued that it looked black. Cari was perceptive at finding inconsistencies in others' arguments. For example, on one occasion she pointed out that to compare our eyes to a mirror is incorrect. She did not change her ideas readily, raising the same question over and over again in subsequent sessions until she seemed satisfied. For example, she constantly asked how it was possible that an observer in shadow could be a receiver of reflected light.

(Note: Whereas Shawn and Paul had very distinct voices, the voices of Cari and the other two girls were more similar, although certainly distinguishable from the voices of the boys. Every effort was made by the researcher during his transcription of the tapes to only list Cari as the speaker when the identification was quite positive, for example, when her name was mentioned. Thus, some of Cari's briefer interjections may have been attributed to anonymous "voices" and may not have been incorporated into her commentary.)

Cari's Ideas Before Intervention

Where Does the Light in This Room Come From?

In her pre-interview, Cari names the lights and the window as the sources of light for the classroom.

How Does Light Help Us See Objects?

Cari writes on her pre-evaluation that, "The sun hits the object and then your eyes. The light lights up the object so you can see it." In her diagram, she draws an arrow from the sun to the tree reflecting to the observer's eyes (Diagram 6). Cari seems quite clear on the nature of reflection and how light reflects from the object to the eye. She does not mention an image and makes no mention of any visual rays of any kind.

In her pre-interview, Cari's response is a little different.

Cari: The light lights up the room and you can see it (the chair). The light shines on the chair.

Researcher: What role do your eyes play, what do your eyes do?

Cari: Your eyes make it so you can see.

Now Cari sounds more like an adherent of illumination. The light "lights up" the room, then you can see the object. Here there is no mention of reflection at all. Her statement about what her eyes do is very general, but, again, she makes no mention of any visual rays from the eye to the object.

In her journal, Cari writes that "Light reflects off the object so you can see the colour". This answer is minimal but she has specifically referred to reflection.

Why Can't John See the Penny in the Bucket?

Cari writes that, "If he looks straight he misses the penny and if he looks down the shadow makes it so he can not see it." She draws two arrows from John's eye, one travelling to the far side of the bucket and one travelling to the near side (Diagram 7). Cari seems to be assuming that John can move in his positioning and so presents a reason for when the side of bucket interposes between the penny and John's eye, that is, "if he looks straight he won't see the penny", and also for another situation when John might lean forward, that is, "if he looks down the shadow makes it so he can not see it. She realizes in the first case that the problem is the side of the bucket but she is not specific about how exactly the side makes it impossible for John to see.

Cari makes a similar statement in her pre-interview about why John can't see the penny.

> Cari: Because this is blocking the penny. It's close to the wall so that when you're looking straight you can only see this part and the bottom of that part.

She describes the side of the container as preventing John from seeing when he is "looking straight", that is, the side is in the way of John's "line of sight".

Why Can John See the Penny After the Bucket is Filled With Water?

Cari writes that, "He can see it (the penny) cause (sic) the water reflects the light to the penny so he can see it." Her diagram shows one ray travelling straight down from the bulb into the water and a "visual ray" from John's eyes through the side of the bucket to the penny (Diagram 8). Cari may have decided that the water makes the bucket transparent, hence the "visual ray" apparently through the side of the bucket. Or she may not have wanted to draw a bent ray because it would not be consistent with her knowledge that light travels in straight lines, yet still wanted to show John's vision "reaching" the penny.

When the researcher asks the same question in the pre-interview using the mini-demonstration, the following conversation develops.

Researcher: Do you see it?

Cari: Yeah.

Researcher: What is the reason you can see the penny after I poured the water? Why can you see it?

Cari: I don't know.

Researcher: Try.

Cari: Because the light reflects off the water or something. I don't know.

Researcher: How is the water different from the air, because there was air in there before?

Cari: The light can reflect off the water, it doesn't reflect off the air.

Cari is puzzled. She does know, however, that light acts differently in water than in air. Her guess is that the explanation might have something to do with reflection from the water but she cannot explain how that might work.

What Happens to Light From the Flashlight After it Hits the Objects?

On the first diagram, Cari draws arrows showing the light reflecting from the mirror. She writes: "The light reflects off the mirror". In the next diagram, she depicts the light both reflecting off and travelling through the translucent glass, using dotted line arrows. For the clear glass, her arrows go straight through. Finally, for the white wood, she shows no arrows but draws what looks like a circle seen from the side right on the face of the wood. The circle is located between and slightly overlapping the two original arrows on

Cari's Ideas Before Instructional Intervention

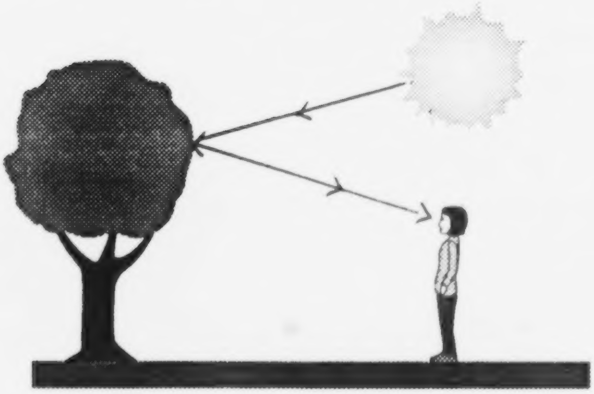

Diagram 6: *Draw arrows to show how light from the sun helps the girl to see objects.*

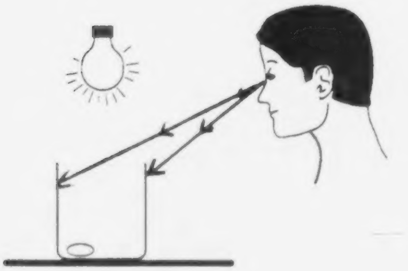

Diagram 7: *Why can't John see the penny in the bucket?*

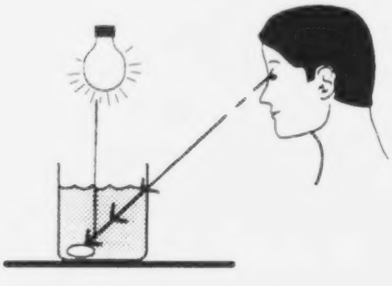

Diagram 8: *Why can John see the penny after the bucket is filled with water?*

the diagram. For three out of the four objects, Cari has a very good understanding of how the light behaves. In the case of the white wood, however, she depicts exactly what she would see if a demonstration had been done for her, that is, a circle of light on the white wood. This circle is evidence for her that the light "stays on" the white wood.

In the pre-interview, Cari 's answers after the mini-demonstrations are similar for the first three objects.

Researcher: When I shine the flashlight on this mirror, what happens to the light?

Cari: It reflects off. It goes off.

Researcher: How about when I shine it on this microwave cover, this translucent object which isn't completely clear?

Cari: Right through it.

Researcher: Does it all go through?

Cari: Some of it will reflect off of it, but most of it will go through.

Researcher: How about this clear plastic? What happens to the light?

Cari: It all goes through.

Researcher: What about on this piece of wood? What happens?

Cari: It all reflects off.

The last response seems surprising. When the light is shone on the white wood there is a visible circle of light on the wood, which in the case of many students is evidence that leads to them assume that the light "stays on" the wood. In fact, the latter is the answer that Cari gave on her written pre-evaluation for the same question with only a line diagram to guide her. It seems more likely that she would give the "stays on" answer after seeing the evidence of the demonstration and the "reflects off" answer when merely looking at the diagram.

Why Does a Black Object Appear Darker Than a Gray Object?

Cari's opinion on her pre-evaluation is that "Gray does not attract as much light as black does." Substitute the word "absorb" for "attract" and she has given the textbook answer. In the pre-interview, she gives the same explanation.

> Researcher: Can you explain to me why this black piece of paper looks darker than the grey bookend?
>
> Cari: Because black attracts more sun. It attracts more light than the grey does. It attracts more sun.
>
> Researcher: Is there another word you could use besides "attract"? Or do you think that "attract" best describes what you're trying to say?
>
> Cari: Yeah, I guess.

Again Cari's answer is scientifically correct. The researcher is trying to see if she will use the word "absorb" but she stays with "attract" which certainly expresses the same idea.

What Does the Coloured Glass Do to the White Light Shone Through it?

Cari selects two answers on her pre-evaluation: "The glass adds red colour to the light" and, "The glass turns the white light into red light". As with the majority of students, she is demonstrating that she holds the view that white light is pure and colourless and that the red is added to the light by the glass.

Cari's answer in the pre-interview is similar.

> Cari: The light goes through the green visor and the visor lets the light go through but the green tints it green.
>
> Researcher: So, what you're saying is all the light goes through but the green tints it green?
>
> Cari: Yeah.

Again, Cari's explanation is that colour is added to the pure, white light by the coloured plastic.

What Colour Will a Green Plant Appear in Green Light?

Cari writes that "The plant will appear green cause the light reflects green." It seems she is saying that the green light will bounce off the plant and come to our eyes, so that we see green. It is not clear whether the green originates in the plant or the light or in both.

What Colour Will a Red Pot Appear in Green Light:

Cari states on her pre-evaluation that, "The pot will appear purple cause the pot is red and the light is green. Red and green make purple. I think." Although she is not sure what colour red and green will actually make, the crux of her explanation is that there is a "mixing" of the green light and the red pigment creating a new colour which is a combination of those two.

Why Does a Blue Book Appear Blue?

On the pre-evaluation, Cari selects the answer, "The light helps our eyes to see the blue colour of the book." Here she is presenting an illumination theory of seeing, coupled with the idea that colour is an innate property of objects. The white light "lights up" the blue book so that we can see it as blue.

She gives the same answer in her pre-interview but becomes unsure of what else to say when probed.

Researcher: This book here, what colour is it?

Cari: Blue.

Researcher: Why does it appear to you as blue?

Cari: Because the light makes me see it blue.

Researcher: In what way does the light make you see it blue?

Cari: It shines light on the book and my eyes and the light...I don't know.

Researcher: Is what you're saying, some of the light shines on the book and some of the light shines on your eyes? Is that what you're saying?

Cari: Yeah, then I can see the book because the light...I don't know.

Researcher: So the light lights it up?

Cari: Yeah.

As the questioning progresses, it becomes clear that Cari is giving the same explanation as the one she selected on her pre-evaluation.

Finally, in her journal, Cari's answer to the question, "Why do objects appear coloured when we look at them?", is "cause the light reflects the colours". Although brief, this answer appears to be consistent with her explanations about seeing the blue book.

Why Are There Only Three Primary Colours of Light? What Are They?

Cari writes on her pre-evaluation that the reason is "Cause if you mix all the primary colours you can make all the other colours." She then guesses that the three primary colours are "blue, red, yellow". Like many of the other students did on this question, Cari is drawing an analogy here between colours of light and colours of pigments.

DISCUSSION OF ALL PRE-INTERVENTION RESPONSES

The students' conceptions about light and colour before the instructional intervention were primarily spontaneous rather than scientific. Only a few students showed any knowledge of the scientific theory of seeing by reflection. When asked how light helps us to see objects, two-thirds of the students conceived of light as something which only illuminates objects. Out of the one-third who mentioned the reflection of light from objects, only four students mentioned that this light was reflected to the observer's eyes. None of these four mentioned images falling on the retina. When completing the diagram of the girl and the tree, twenty-one of the students drew arrows which indicated an illumination conception of seeing, with two-thirds of these diagrams being supplemented by some type of visual rays, that is, seeing is something which goes from the observer to the object. The latter addition follows from the illumination idea because if light is not reflected to the observer's eyes, then the only way to connect the observer and the object is in the other direction, that is, by showing something traveling from the eye to the object. When trying to solve the penny problem, only one student exhibited a scientific conception. Of the rest of the students, half demonstrated that they conceived of a "line of sight" from the observer to the penny. Again, this follows from having an essentially illumination conception of the role of light in seeing. The other half totally reinterpreted the problem so that the hidden penny was not hidden, and thus did not deal at all with the question of why the observer could not see the penny. This meant that their conception of seeing remained unexplained. Their reinterpretation of the problem may be an indication of their difficulty in coping with it.

It should be noted that questions such as the penny problem are specific applications of a general theoretical understanding of how light helps us see objects. To answer them, students must transfer and apply the general theoretical principle to an unfamiliar situation. Such application questions can potentially be measures of understanding because mere memorization of the general theoretical principle will never be sufficient for answering them. That is, a student may be able to write down a general statement of, for example, the reflection theory of seeing, which she has memorized. Reading such a statement an evaluator may assume that the student understands the concept. However, when the same student has difficulty in solving a problem by transferring this conception to an unfamiliar problem such as the penny problem and applying it in a creative way, her "understanding" may be questioned. The need for a deeper understanding in order to apply a general theoretical principle to a specific and unfamiliar example, may explain why, when moving from the general conception of seeing to the specific application, the number of students who articulated a scientific understanding of how light helps us to see objects or why objects appear coloured when we see them, dropped off sharply.

Asking the question of what happens to the light after it hits each of the four objects allows insight into the children's understanding of the nature of a reflected image. Almost all the students were able to depict a scientific explanation of what happens to the light after it hits the mirror and after it hits the clear glass. On the other hand, almost all students held spontaneous conceptions of how a beam of light behaves when it hits the other two objects presented, that is, the translucent glass and the white wood. For the translucent glass, two-thirds of the students saw the light as "staying on" the glass or as traveling straight through it. Only seven students saw the light as both traveling straight through and reflecting. Six of these last seven students, however, depicted the light as both traveling straight through and as reflecting coherently. All the above explanations are spontaneous conceptions of what happens. The remaining one of these last seven students seemed to depict both the light traveling through and the reflected light as scattering after hitting the translucent glass. He was the only one who appeared to have a scientific conception of what happened to the light after it hit the translucent glass. Almost all the students also held spontaneous conceptions of what happens to the light after it hits the white wood. Thirteen of the students predicted the light would "stop" on the wood, five predicted it would both absorb and reflect, and eight suggested the light would reflect off the wood. Four of the latter eight depicted the light as reflecting coherently. These are all spontaneous conceptions. The remaining four students of the latter eight drew diagrams which seemed to depict the light scattering as it reflected. These last four, then, are the only ones who might have held a scientific conception of what happens to the light after it hits the white wood.

In the above group of questions, the explanation of the behaviour of light varies in difficulty depending on the object. The mirror and the clear glass are easy for the children to explain scientifically because both are familiar objects and all students have had experiences of direct observation sufficient to provide the basis for an explanation of how light behaves after it hits the object. The translucent glass presents a more difficult problem because it is not such a familiar object. Some students treated it as opaque, some treated it as transparent, and the remainder as both. Only this latter group mentioned that light both reflected and passed through. The white wood presented the most difficulty. Although it is not an unfamiliar object, when light shines on it the visual evidence of the light is misleading. That is, the observer sees a "circle" of light on the wood but sees no visual evidence of reflection. Relying on direct observation, then, leads to conceiving that the light "stays on" the white wood, rather than reflects off. Half the students gave such a "stays on" response. To give the scientific conception that the light reflects off the wood requires the application of the general theoretical principle that light reflects off all visible objects.

Except for two of the questions on colour, the vast majority of students displayed spontaneous conceptions when answering questions related to colour. One of the exceptions was the question asking why black looked darker than grey. On this question, ten of the students suggested colour was innate, a spontaneous conception, while fifteen gave an explanation in scientific terms of absorption and reflection. The other exception was the question asking why the blue book appeared blue. On this question, fifteen of the students chose a spontaneous conception from the alternatives given, while ten students chose the scientific conception from the alternatives given. For the rest of the questions, spontaneous conceptions predominated. In response to the question about what the red glass does to the white light which passes through it, twenty-two of the students selected one of the alternatives which suggested that the red glass "adds" colour to the white light. This is a spontaneous conception. Only four students selected the scientific explanation that the red glass lets red light through but stops all the other kinds of light. Responding to the question asking the colour of the green plant in green light, twenty-three of the students did not mention reflection of light by the plant, implying an understanding of colour as an innate property of objects. Three students mentioned the reflection of green light by the plant, a scientific conception. In response to the question concerning the colour of the red pot in green light, all of the students suggested either that the colour of the object or the light would dominate and determine the colour of the pot, or, that the colour of the light would "mix" with the colour of the pot to produce a new colour. Again, this implies a spontaneous conception of colour being an innate property of objects, rather than a scientific conception of the appearance of colour being a result of the interaction between light and colour through absorption and reflection. All of the students who tried to give a reason for why there were only three primary colours of light answered descriptively by stating that the three colours could mix together to produce all the other colours. They also, in most cases, named the three colours as blue, red, and yellow, the three colours of pigments. None of the students gave the scientific explanation that the three primary colours of light corresponded to the three types of colour-sensitive cells in the retina of the human eye, nor did any students correctly list the three primary colours of light as red, blue and green. For these two questions then, all the students displayed spontaneous rather than scientific conceptions.

The answers to the questions on colour also showed a variation in conceptual difficulty. Over half the students gave a scientific explanation of why a black object appears darker than a grey object, mentioning one or both of reflection and absorption. Also, one third of the students chose the scientific explanation of why the blue book appears blue. In the latter case, this might be explained by the fact that it was a multiple choice situation. However, only four students chose the scientific conception for why the light appeared red on the other side of the filter, yet this was also multiple choice format. A more likely explanation is that, again, the "black-grey" question and the "blue book" question are general in nature and ask for knowledge of a general theoretical principle. That is, questions such as these could be answered by simply restating rote knowledge. In comparison, the two questions concerning the green light, the green pot, and the red pot, are, like the penny question, specific applications of general theoretical principles to new situations. Thus, they are much more difficult to explain. Not only that, they represent situations not commonly encountered and thus observed, that is, few people ever have the opportunity to observe coloured objects under monochromatic light. The questions concerning the three primary colours of light represent a different type of difficulty. Giving the scientific answer here requires either great insight or a degree of specialized knowledge which is not generally part of the repertoire of the average adult, let alone the average child. In fact, the theory that the eyes contain three types of colour-sensitive cells was first put forward bv scientists only about two hundred years ago, and not empirically verified until about twenty-five years ago.

HISTORY OF SCIENCE

Children's spontaneous conceptions about seeing, and colour do have parallels with the history of science but do not demonstrate a one-to-one correspondence. This can be seen by briefly comparing students' spontaneous conceptions with the historical development of ideas about seeing and colour (see Appendix C). As Ronchi (1970) and Lindberg (1983) point out, the basic question about vision which concerned the Ancients, that is, the Graeco-Romans, was that of what happened between the object and the eye. The main theories put forth to answer this question were that rays emerged from the eye; that bodies emitted "images" of themselves; that something emerged both from the eye and the object; and that contact between the eye and the object could be established by some sort of intervening medium, usually air. In none of the above theories, even that involving "images", was it suggested that light played any role other than that of illuminating the object. The images suggested by the Ancients were characterized as extremely thin outer layers of the object which detached themselves and flew through space to the observer. This intuitively correct idea, however, was never directly connected with the reflection of light by the object. The latter idea was not seriously considered until the tenth century, when Al-Hazen first put forth the basic principles of the modern scientific theory of seeing. Like the Ancients, the majority of the students in the study held spontaneous conceptions about seeing which treated light only as something which illuminates objects. Further, in their attempts to explain how we see, that is, to connect the object and the eye, some of the students also referred to "view" and "line of sight", concepts which show strong parallels with the Ancient's ideas of visual rays that is, of something which emanates from the eye and travels to the object.

Students' spontaneous conceptions of colour also showed parallels with early ideas in science. The Ancients held that colour was an innate property of bodies. Ptolemy suggested that colour is an inherent property of bodies, a layer on them. Aristotle described colour as overlaying the surface of objects. This idea of the innate nature of colour predominated well into the seventeenth century: "In all the philosophy of the previous centuries (before Grimaldi) the interpretation of colour presented serious difficulties. Many strange and discordant ideas had been put forward, but all seemed to agree on one point: that light was something quite distinct from colour....Colour was a quality of the object" (Ronchi, 1970, p. 41). Further, the key assumption connected with this idea, that white light is pure and colourless and can only be seen as something which illuminates coloured bodies, was not seriously questioned until 1704 when Newton published his ideas and results and laid the foundations of modern colour theory. Newton demonstrated, using prisms, that white light was a combination of all colours. He connected this observation to colour, and concluded that bodies appear coloured because of their tendency to reflect one kind of light more than another (Newton, 1931). The spontaneous conceptions of the students in the study about colour were basically pre-Newtonian conceptions. The students also treated colour as an inherent property of bodies. They assumed that white light is pure and colourless and treated white light only as something which illuminates already coloured bodies.

A specific example of the parallel between students' spontaneous conceptions and the history of science is student explanations of the "penny experiment". This experiment is first described in the works of Ptolemy, who wrote extensively on optics. Ptolemy's theory of vision was that a material flux extended from the eye and went out to the object. In other words, he held a "visual rays" theory of seeing. Ptolemy explained that the penny was visible after the container was filled with water because the visual ray of the observer was bent when it entered the water and could now reach the penny. This bending or refraction created a link between the observer's eye and the object. Many of the students in the study gave Ptolemaic explanations of the penny experiment. That is, they suggested that the reason John could not see the penny was that the side of the container blocked his "view". Explaining why John could see the penny after the container was filled with water, the students suggested that the water "reflected" the penny to a new location where it was once again in John's "view". Unlike Ptolemy, then, the students did not directly use the concept of refraction in their explanations, probably because they did not understand it. In their conception, the water "moved" the coin, rather than bent the "line of sight". One student in the study, however, did actually suggest that the visual rays were "bent" by the water so as to reach the penny.

Another specific example of the parallel between students' spontaneous conceptions and the history of science is in the physiology of colour vision. Students were asked on their pre-evaluations to explain why there were only three primary colours of light. All the students who answered the question stated that it was because mixtures of these three colours could make all the other colours. This answer, however, only describes what the three primary colours do. It does not explain why there are only three colours. The scientific explanation for the three primary colours was first developed by George Palmer, who published his ideas in 1777. It was later further developed by Thomas Young. Palmer stated that the surface of the retina contained three kinds of "particles" analogous to the three primary colours. These "particles" were colour sensitive to their own rays, and sensations of colours were produced by differing motions of these colours. Palmer's theory was not empirically confirmed until 1964 when it was established that the retina does have three different kinds of colour receptors, called cone cells. The pigments themselves were only isolated in 1985 (Montgomery, 1988). It is clear that none of the students in the study held anything other than "pre-Palmerian" conceptions about the primary colours because their answers totally excluded explanations based on colour receptors in the eye. This is not surprising since such an idea came "late" in the development of colour theory and could logically be expected to require the grasp of other preliminary ideas, such as seeing by reflection. The students in the study were unable to explain why there were only three primary colours and not some other number, just as scientists were unable to theoretically explain the same phenomenon until as recently as two hundred years ago.

Part Two: Students' Conceptions During Intervention

The most difficult aspect of evaluation is evaluating the process of learning. That is, it is difficult to evaluate what is occurring while learning is taking place. It is not as difficult to evaluate the starting points and the products of learning. This is one reason why evaluation in schools tends to focus on products. Typically, a measure is made of what the student "knows" before the learning starts and then a new measure is made of what the student "knows" after the instruction has ended. The difference is a measure of "how much" the student has learned. Although necessary and valuable, unfortunately, such evaluation sometimes tells us little about what actually occurs during learning. Specifically, it gives little insight into what kind of learning is taking place, how learning is taking place and, thus, into how deeply students actually understand what they are supposed to be learning. Methods have been developed, however, to try to remedy this situation. One method used in learning research is protocols or think-alouds where students engaged in problem-solving are asked to verbalize the thinking they are doing as they try to solve the problem. In classrooms, for example, students can work in dyads for problem-solving and "talk through" their solutions while their partners listen. Another method of investigating what happens during learning is to use response journals. Students are asked to make daily, diary-like entries about their particular learning. These entries can involve words and/or pictures. This journalling method has been used in language arts for some time now but is quite new in science. It was used in this study. A third method is keeping track of what students say during whole class and small group discussions using audio tapes. The study also employed this method. The main data sources, then, for what happened to students' conceptions during the study, were the daily journal entries of all students and the transcripts of the whole class and interview group discussions.

RESPONSE JOURNALS

The students were asked to write daily entries in science response journals following each session. The purpose of the response journals was to give access to the changing ideas of all students. This was not the case with the whole class discussions since not all students participated and not all students participated to the same degree. Nor would it be the case with the interview group discussions since these only involved five students. The students were asked to make their journal entries in response to two general questions. These questions were, "How do we see objects?", and "Why do objects appear coloured when we look at them?" (see Appendix A, p. 3). The instructor did not make any contributions to any of the journals but merely collected them at the end of the study. No limitations were placed on format or length regarding entries. Students were asked to try to give evidence of how their ideas changed over the course of the instructional intervention. Journal entries showed considerable variation in format and length. Some students used only words, some used only diagrams with labels, some used both words and diagrams. Most entries were brief. Students often simply wrote that their ideas had not changed. This was given as an option when instructions for the journals were given. In fact, out of four hundred eighty possible entries (assuming two entries per thirty students after each of eight lessons and ignoring absences), two hundred thirty entries stated that extant ideas had not changed. Thus, the actual written and diagrammatic information from the journals about changes in student thinking represented about one-half the possible entries.

Individual Journals

One student, Derek, started out by writing that the eyeball receives a message from the brain to open the pupil to limit the amount of light that enters the eye, the eye reflects the light and then it turns into an invisible beam that breaks up, then the eye reads this beam. Objects appear coloured because of the shade of the reflection, then the eye turns it into a colour. Next, Derek drew a diagram of an experiment to prove his theory of seeing. It involved shining a beam of light on a model of the girl and the tree. Later, Derek asked, if we see by reflection, where does the light go after the eye has received the image. He wondered why it didn't shoot out of the eye again in a "floppy beam". Derek's explanations are a little confusing. He relates seeing to the function of the eye and colour to reflection but retains a conception of something shooting out of the eye after seeing.

Maurice first drew labelled diagrams of the reflection theory of seeing and the reflection theory of colour. Later he wrote that he still thought it was reflection. He ended his journal by saying "I was right with both of them". Maurice begins and ends with a scientific conception.

Gary started off by describing both the reflection theory of seeing and the reflection theory of colour. He designed experiments he thought would prove both his theories using a laser beam but was unable to obtain a laser. Later he added to his theory of colour by noting that white light is made up of all colours and that objects reflect a particular colour from the white light. Finally he added the idea of the colour sensitive cones to his reflection theory of colour. Gary has scientific conceptions of seeing and colour right from the beginning. He retains these and is able to add two new scientific ideas to his understanding, that is, white light is made up of all colours and the eyes contain colour-sensitive cones.

Barbara first wrote that we see objects by illumination and that we see colour by reflection. Later, she wrote that we see objects because some light is absorbed and some light is reflected off them onto our eyes. Later still, she added the idea of an image which goes to the back of your eyes. In her final entry she explained that white light is made up of all colours and that objects only absorb certain of these colours. Barbara begins with an illumination theory of seeing and a reflection theory of colour but ends with a reflection theory of both. She also adds two new ideas, that of an image and that white light is made up of all colours.

Monty initially drew a diagram of a "two way" theory of seeing, that is, he showed light from the sun bouncing off the tree to the observer's eyes and a "line of sight" back to the tree. His initial entry on colour stated that objects only let out certain colours of light and absorb all other colours. All the rest of his entries stated that his ideas had not changed. Monty sees no inconsistency between his "visual rays" theory of seeing and his reflection theory of colour. He holds to his initial ideas throughout the study.

Donald began by writing that objects absorb and reflect light and that our eyes take in the reflected light. He wrote that we see colour "through our eyes". For his next entry he wrote that change and difference in colour outlines the shape, and that objects reflect colours and the colour they reflect enters our eyes. The following entry he added that sunlight lights up objects, we concentrate on them, and the reflected colour enters our eyes. He also repeated his previous statement about colour. Later, he suggested that we see "through all four theories". He also repeated that we see colour by reflection, and included a diagram. Then he wrote that we see through reflection and illumination. Finally, in his last entry, he stated that, "without light there can be no sight and without sight we won't see the light". Donald begins with scientific conceptions of seeing and colour but questions them. He seems unable to completely get away from the idea of illumination as something separate from reflection.

Zelda first wrote that people see objects because there is light on them. For colour, she explained that colours form by reflection of light off moisture in the air. Later, she repeated her theory of seeing, stating that the sun's rays shine on everything and then we see through our eyes. Finally, she wrote that people see by reflection because "there is a screen at the back of your eye that will reflect what you are looking at". Zelda achieves some scientific understanding of reflection and of the retina during her participation in the study but in general her understanding appears incomplete and unsystematic.

Miles' initial entry stated that some light reflects off objects into our eyes and that objects appear coloured because they take in any colour except "the colour itself". Next day he simply repeated the above. Later he asked why you can still see the light on a sunny day even though your hands are covering your eyes. Following that, he suggested that light "goes through colours". Finally he added that this was so because light absorbs all colours. Miles retains his scientific conceptions throughout the study.

Sam began by writing that we can see objects because light reflects off them, and that "some objects absorb some of the light and that makes them different". Next day he repeated his comment about seeing but explained his ideas on colour further by writing that the light not absorbed is the colour we see. The following day he combined seeing and colour by writing that the light which reflects off the object to our eyes "forms a colour". The next day he suggested that we see by the "two-way" theory. Following that he restated his theory of seeing as "light reflects off objects and we see them". The next day he pointed out that light both brightens the object and reflects off it, and that objects absorb a bit of light and reflect the rest. Finally, he concluded that "The object absorbs all colours except its own and reflects it." Sam seems to work out and clarify his scientific ideas as the study progresses, considering certain ideas, then rejecting them in favour of others.

Richard started by writing that seeing involved the eye and the brain and the illumination of objects by the sun. He did not understand how we see colour but thought that our eyes and light were involved. Next day he suggested that we need all four student theories to see all objects. Later he wrote that the whole business of light was "strange" and "screwy". He ended by commenting that "This is very hard to understand and is confusing". Richard is unable to clarify some of his ideas. His main stumbling block may be that the light image makes no sense to him.

Heidi first wrote that we see by reflection because to see there has to be some kind of light. Her diagram showed light reflecting from the tree to the observer's eyes. She suggested colour is seen when light reflects off moisture in the air, like the rainbow. Heidi found the idea of visualizing an image "very strange". To try to understand it she compared it to the image in a mirror. Later, Heidi wrote that "we see colour from the light and how it interacts with the light". Her final comment was that seeing images is the way we really see. Heidi begins incorporating the idea of an image into her conception. She also begins connecting colour with light.

Tricia initially wrote that we see objects by looking at them and by the light reflecting off them. Objects appear coloured because they are "dyed" and light reflects off them. Next day, she suggested that light reflects off the object and you see the light and the object. Her diagram showed light reflected to the eye of the observer and also a "line of sight". She explained that objects appear coloured because light reflects off them and shows the colour. Later Tricia wrote that we look at objects and see images. She also had a question: "How did scientists find out that animals are colour blind?" Finally, Tricia explained that a green coloured object reflects green and absorbs all other colours, adding that light is made up of all colours. Tricia acquires a more scientific understanding of colour and why objects appear coloured. She becomes interested enough to ask about colour blindness. She is unable, however, to apply her ideas about reflection to seeing and adheres to an illumination-visual rays conception throughout.

Eleanor started off suggesting that to see we need eyes and light. She reiterated this later, stating that light shines on everything and if there was not light we could not see. She made only one truncated comment on colour about halfway through the intervention: "Because if a tree or object absorbs light". Eleanor's journal reveals little about her ideas and how they changed, except that she considers light very important for seeing.

William's initial idea was that light reflects objects and comes to our eyes. For colour he used an example: "The apple reflects red light and absorbs other colours". Later, he gave another example for colour, a tree, mentioning that both green and brown are reflected. William later suggested that light comes down as illumination, turns into reflection, goes into our eyes, and turns into visual rays. He also asked a question: "When you see an image and it's really there, why do you see a mirage?" William described the experiment where white light is shone through a combination of three coloured filters and comes out white again. He reasoned this was because white light is all colours. Finally he explained that a red object looks black under green light because the red object absorbs the green light. Except for his insistence on visual rays, William begins with and maintains scientific conceptions of seeing and colour. He is able to understand and explain the scientific implications of some experiments on colour.

Susan drew a person "looking at" a tree and the upside down image of that tree inside the person's head. She wrote later that "Light has to do with colour because of pigments", and, finally, "Colour is reflection". She concluded that she had trouble putting her thoughts in words. Susan picks up some ideas but has trouble systematizing them in words.

Jody first wrote that seeing involves the eye and light. She thought colour might have something to do with a "special kind of fluid in our eye". Later, she wrote brief comments about seeing: "From their eyes", and about colour: "Maybe because of the light". She disagreed with the idea of an image "because you can touch it and images you can't touch". Finally she concluded that light is the way we see. Jody's comments are speculative and brief. The only things she is sure about are that our eyes and light have something to do with seeing and that we don't see images.

Laurie initially wrote that we saw because of our pupil and objects appeared coloured because we have primary colours in our eyes. Later she suggested that people see objects by the "two-way" theory, and that we see colour because we see "all the colours except for the colour that it is." Then she changed her theory of seeing to reflection. She added later that she still thought "we are all upside down and everything". She concluded that we see colour because the colour that it is "stops the other colours from going through". Laurie thinks about the different theories of seeing and settles on reflection of some kind. She begins to grasp that objects appear coloured because of reflection and absorption but has trouble expressing this clearly until the end. She plays with the idea of whether the observer or the image is upside down.

Ian began by writing that we see objects because light shines on them and that objects appear coloured "because that's what colour is". Later he felt that the four student theories expressed stages of seeing going to reflection. He explained the colour of objects by saying that light shines on them and "it all goes to reflection". Finally, he explained that one colour is absorbed by the object and all the others are reflected. As an example, he wrote that black absorbs all colours. Ian eventually comes to accept the idea of reflection for both seeing and colour. He does not explain much about seeing by reflection. He does elaborate on seeing colour due to reflection and absorption, although he does not seem clear on how to consistently apply each concept to examples.

Hugh drew a diagram showing an object, an observer, and an image of the object upside down in the observer's head. He explained that colours are shades of light. Later he stated that he believed his experiment to prove the two-way theory of seeing was correct but he does not describe the experiment. The next day, however, he wrote that the researcher had convinced him the reflection theory was correct. Later, he wrote that colour is a result of the way objects interact with light. His last entry was that white light is all colours. Hugh's comments are brief. His ideas about seeing pass through different conceptions to reflection. He does not say much that is specific about colour but he does note that white light is not pure and colourless.

Hilary first wrote that we see objects because light illuminates them and that objects appear coloured because "light reflects a certain sort of coloured (sic)". Her next entry reaffirmed her initial conception of seeing. She also reiterated her conception of colour more clearly: "The light reflects off colours so that we can see it." Later Hilary suggested that we see objects because light reflects off an object, goes into the eye upside down, and the brain flips it up. She also later expressed doubt about her ideas on colour: "They don't necessarily because it could be white light that just looks like it's coloured so I'm confused". She stated more developed ideas in her last entry, writing that white light is all colours and whatever colour the object is "will only go on the object". Hilary's ideas undergo significant changes from her spontaneous conceptions. She finishes with a scientific conception of how we see and seems to have a scientific conception of why objects appear coloured, although she still has trouble expressing it clearly.

Janet initially explained that we see things because of the pupils in our eyes and that objects appear coloured because "the colours reflect it and its colours go back to the light". She later added to her seeing explanation, stating that "things are reflected so we have the light to see things". This was followed by another addition which pointed out that the sun lights things up. Later she stated that we see colour because our eyes absorb the colours. She then added that we see things sometimes "because the light reflects things", and that objects look coloured because there are different colours. Next she wrote that when we see, the sun does all the work and our eyes do no work. She also asked why nearby objects did not appear upside down in her telescope. Later she repeated that our eyes absorb the colours, and also wrote that some colours make up other colours. She described how the white light again appeared white after passing through a certain combination of three coloured filters. Her final entry mentioned the cones in the eyes and the three primary colours of red, green, and blue. Janet acquires a number of new ideas during the interventions but is not able to systematize and to describe them clearly.

Allison drew a labelled diagram which suggested that we see because light bounces off the object and into and "behind" the eye. She drew the same diagram for why objects appear coloured. Later she selected the two-way theory as the best depiction of how we see. Following that she drew a more precise labelled diagram for colour, showing that objects appear coloured because they absorb all the colours of light except the one which they appear. Finally, she drew a labelled diagram showing how a prism breaks white light into colours. Allison begins with an understanding of reflection and the eye, but still adheres to a two-way theory of seeing. Her diagrams relating to colour show that her conception of colour is becoming more complete and scientific over the course of the intervention.

Wendy first suggested that we see because our eyes are like mirrors and objects reflect into our minds. Later she explained that objects appear coloured because the light reflects onto an object and then bounces into our eyes. She expanded on her conception of seeing by adding that an image is carried into the mind and then to the brain. Further on, she stated that she did not understand how white could be all colours. For her final entry she wrote that "white light reflects onto other colours", and drew a diagram depicting that a red object in green light appears black. Wendy concentrates on the roles of the eye and the brain in seeing. She incorporates the conception of an image. She also begins to grasp the reflection theory of colour, although she is puzzled about the nature of white light.

Colleen first wrote that objects appear coloured because "light shines on the object which goes to our eyes and then when we look at the object it is coloured". Her next entry stated that it is hard to write "about something you know nothing about". Later she stated that the two-way theory confused her because the reflected light should hurt the observer's eyes. She added that there must be a special part of the brain that helps us see colours. She subsequently described her theory of seeing as light reflecting from the object and hitting the observer's eyes, then reflecting off the eyes "and then you see the tree". Later she added that we see objects through images but wondered if this was really true. She concluded in her final entry that she still really had no idea of how we see colours. Colleen begins to achieve some understanding of reflection and of images but ends up unsure if her ideas are correct.

Mark initially wrote that we see with our eyes and that colour is a property of objects which our eyes see. Subsequently, he partially expanded on this by saying that we see by the light reflecting off the object and hitting our eyes, but repeated that colour is something we just see. Later he wrote that we see things by seeing images. His last two entries on colour again reiterated that colour is just something we just see. Mark's ideas about seeing seem to change and develop but his ideas about colour remain the same.

Matt started off explaining that we see objects "with a special nerve in the eye". Objects look coloured because light bounces off them into our eyes. Later he drew a diagram and wrote that we see by two way and reflection combined. He added that we see colour when the object "lights up". His final entry on seeing stated that we see by reflection, while his final entry on colour suggested that we see colour by shining a white light on "many other colours". Matt's conception of how we see changes to include light as well as the eye, then settles on reflection. His ideas about colour remain the same.

Nora's initial conceptions were that light helps people see things and that objects appear coloured because they are coloured. Later she altered her conception of seeing and suggested that the sun's rays bounce off the object, hit our eyes, and bounce back onto the object. She repeated this in her final entry on seeing. She then made two further entries on colour, one referring to the special cells in our eyes and one which stated that when coloured light hits the object it will turn it a different colour. Nora's ideas about seeing became more scientific. She adds new ideas about colour but is unable to integrate these into a new over-all conception.

WHOLE CLASS DISCUSSIONS

The whole class discussions with the students about seeing and colour occurred mainly after the session on seeing theories, after the session on seeing by reflection, after session on evidence for colour theories, and after the session on colour by reflection. There was no time available for discussion after the evidence for theories of seeing session. After the session on theories of colour, the students preferred to discuss the experiments they might do and the materials they would need to do them. Twenty of the thirty students participated in one or more of the discussions at one time or another. Participation was deemed to mean that the student spoke at least twice in succession during an exchange of ideas concerning seeing and/or colour. One student participated in nineteen exchanges, eleven students participated in nine to four exchanges, and eight students participated in three or fewer exchanges. The exchanges tended to focus around certain questions which were raised again and again, sometimes by the same student but more often by several different students. The questions raised included the nature of light and darkness; what happens between the eye and the object; the eye's reaction to light; the nature of the image; the nature of white light; the colour of objects under coloured light; and the reasons for the colours of certain phenomena. The clarification of these recurring issues was obviously important to the students in their attempt to gain a better understanding of how we see and why objects appear coloured. For this reason they provide one way of looking at what happened to the students' ideas during the period of the instructional interventions.

The Nature of Light and Darkness

Richard: We can see in the dark. Some people can see in the dark.

Researcher: Can you give an example of that?

Richard: If you go in a really dark place where there's no windows or light or anything, as soon as you touch something you feel what it is and then you picture it and you can sort of see it like a picture.

Richard is questioning whether we really need light to see. However, his definition of darkness is based on eliminating only direct sources of light. He also neglects to consider the role of memory.

Hilary: We can't see in the dark because there's no light. I think Allison is right that it's the two-way and the reflection put together.

Researcher: What about creatures that hunt or live at night like owls. Can we say they're actually in the dark or what or are we talking about a matter of degree here?

Maurice: No because the moon is up and the stars and there's light, not a lot but enough so you can see.

Hilary is sure about the need for light to see. Maurice points out the role of indirect sources of light.

Richard: We have a bathroom in our house and it's got no window in it, right, and at night if you close the door and everything you can't see a thing. Oh we have white tiles in the shower and you can sort of see the shower.

Ian: Yeah, that's because the light comes under the door and in the crack. In my bathroom there's a crack that big under the door and at night light comes under.

Hilary: You also remember it, Richard.

Richard pursues his point. Darkness seems to be an either or question to him rather than a matter of degree. Ian points out how light from secondary sources actually does get into the bathroom. Hilary reminds Richard that he is familiar with what is in his bathroom and so knows what is there even if he can't see very well.

The above exchanges are important because they lead to consideration of the role of light from non-direct sources. It is important to realize that light is constantly coming from all directions and constantly reflecting off objects. This leads to considering light as more than something which shines down directly on objects and illuminates them. The realization of the reflective behaviour of light is a key step in understanding how we see objects, that is, by light reflecting off them to our eyes.

What Happens Between the Eye and the Object?

> Allison: Well you see the tree (inaudible) and you see the tree also because the sun will shine on the tree and then you see the tree and it will go in backwards into your eyes and it will be upside down and then it will turn right side up and then you'll see it with your eyes.

Allison has some understanding of the scientific conception of how we see and how images fall on the retina. But she continually refers to "seeing" as a separate act: "And then you see it".

> Derek: The light of the sun hits your object, comes back here and hits almost like something in your eye and it bounces back. Then it comes up again and then your brain absorbs the object and turns it right side up.

Derek also has some conception of the reflected image and the role of the brain. But he too treats seeing as something to be added on when everything else is done. After the light enters the eye, he suggests, it then bounces back out to the object.

> Hugh: I think it's the two-way because it isn't one it's all of them, sort of combined. Like the sun's shining on the tree, the light is on the tree,

> you see the tree with visual rays sort of like reflection, the light bounces off the tree back to you like the two way, and you see the tree. There's reflection, light is shining on the tree and there's reflection.

Hugh also has to insert seeing into his reflection description as a separate act in order to make the process of seeing sensible to him. He makes a specific reference to visual rays.

> Eleanor: In two-way reflection you're looking at the tree twice if it's that way. The sun's shining on the tree, the light bounces off the tree, you see it, then you look back at the tree. That doesn't make sense because if the light goes into you then all you have to do is (inaudible).

Eleanor is trying to put her finger on what she sees as a contradiction in the reflection plus seeing type of explanation. The contradiction for her is that such an explanation makes it sound like you should see the object twice. That would be unnecessary and also does not correspond with her experience.

> Sam: I think it's the two way because when the sun goes on it you need a little bit of light to reflect so you can see it and you gotta look at it.
>
> Researcher: What does it mean to "look at" something?
>
> Sam: Well, sort of focus on it, like I want to look at that list, I'm not looking at you but (inaudible) focussed on it.

Sam still adds "looking at it" after the fact. A possible source of this idea now emerges. The act of focussing on an object is equated with "looking at it".

> Allison: No, but it doesn't make sense how you see the image because if you're looking at the person....If I turn my back on you I wouldn't be able to see you because you have to be looking at the person or whatever to see the image. So something has to come out of your eye to see.
>
> Researcher: Okay, well that's again the way we talk. We say, "You're looking at me" but what's happening, according to the reflection theory,

is that you are seeing the reflection of the light bouncing off me. So it's sort of like my image is coming to you, you're not looking at me. And again it's the way we talk that gives us these ideas. So when you say, "You're looking at me", it implies that there's something coming from you to me.

Allison: But still if I turn my back to you the light would still be reflecting off to you, but I wouldn't be seeing you.

Researcher: But your eye wouldn't be in a position to receive it.

Allison: But you have to be looking at the person to see them.

Researcher: Okay, I would say that your eye has to be in a position to receive the reflected light.

Allison: Okay.

Allison brings out the nature of the problem in understanding the connection between the eye and the object very well. The source of her need to postulate something coming out of the eye is her knowledge that we can't see things without "looking at them". Everyday language supports her conception, that is, we talk about "looking at things", not about receiving reflected light. At the end of the exchange she seems to be considering another way of thinking about what "looking at something" means.

The Eye's Reaction to Light

Monty: I kind of object to the reflection because if all that light goes in your eye it's going to make you blind.

Monty puts the issue in a nutshell. He knows from his own experience that looking directly at light hurts the eyes. He applies this knowledge to reflected light and raises an objection to seeing by reflection.

Hilary: I don't really think it's reflection because when it's sunny outside and you go out skiing and there's lots of snow then the sun reflects off the snow and when you look at the snow if you don't have any sunglasses on it hurts your eyes because it makes it look really bright. So I don't think....

Researcher: So you don't think that's reflection?

Hilary: Yes I think it is reflection but that's why I don't think reflection's the way you see because if it was it would really hurt your eyes because of what it does to the snow then it does to everything else.

Hilary raises the same question as Richard but much more comprehensively. She uses an example from her own experience, then draws a conclusion from it. Following her remarks the researcher suggested that there might be differing amounts of light reflected to the eyes and that the snow could be an "extreme" example. Hilary agreed this might possible.

Susan: (The tape is quite inaudible but the researcher recalls from the few words that can be made out that Susan describes how our eyes slowly get used to the dark after the light has been off for awhile.)

Researcher: What do you think that might be because of?

Susan: Reflection.

Researcher: Have you ever looked at a person's eyes in the dark and in the light?

Susan: Yes.

Researcher: What happened?

Susan: The more light your eye gets smaller.

Researcher: Why might your eye get smaller when it's light and bigger when it's darker?

Ian: You don't need as much light in the day and then you need, you're trying to find light when it's dark out.

The knowledge that the eye adjusts to differing amounts of light provides a possible explanation for why reflected light may not damage the eye, and thus gives the reflection theory new credibility.

> Allison: With the owl. Well, like when you're in a dark room the pupil opens wider to let in more light so if you were in a dark room and after awhile your pupil would get bigger and you'd be able to see whatever there was.

Allison gives a clear summary of the eye's ability to react to differing amounts of light. An understanding of this ability helps to diminish the force of the "eye damage" objection to the reflection theory of seeing.

The Nature of the Image

> Donald: Why isn't it when I'm standing here everything doesn't go....why aren't we just seeing everything upside down?

The idea that our brain "flips" the image makes no sense to Donald.

> Hugh: Like you said that light brings an image of the object to your eyes.
>
> Researcher: No I said light is the image.
>
> Hugh: Is the image.
>
> Researcher: Yeah, not brings, it doesn't carry it, it is the image. But I'm glad you said that because it's a really important point. Cause you would probably say that you should see light carrying something to our eyes. But no, light is the image.
>
> Hugh: How can that be, how can light be an image?

Hugh's question encapsulates the most difficult problem facing the students in their attempt to grasp the scientific conception of how we see. The notion of an image does not make much sense to them at all.

Eleanor: If you say that everything, that light is the image, then we never really see anything, we only see images. Then we never see a thing.

Researcher: Well it would be the same as saying when I speak to you you never hear a thing all you hear is sound waves.

Eleanor: But we are hearing.

Researcher: When somebody talks to you on the telephone you don't really hear their words because their words are translated into electrical impulses that go through the wires and come out the other end and are turned back into words again, so you never really hear what they say. So I'm not sure if that's a fruitful line of enquiry. But I guess you could say that, yes, we see images of objects. We don't just see images, we see images of objects. Those objects are really there.

Eleanor: But we don't see them

Researcher: We see them, yes we do see them.

Eleanor: Then that can't be an image.

Voices: Eleanor!

Eleanor: Well he's saying that light is the image, right?

Researcher: Yeah.

Eleanor: That is an image right? So if I look at him I'm not really looking at him I'm just seeing an image of his face.

Researcher: You're seeing him through an image, I guess. It's a good point, though.

This is an extremely intriguing discussion. Eleanor knows from her own experience that objects exist and that we see them. Now she has just been told that the actual mechanism of how we see is that light reflects from the object and that the retina of the eye receives a light image of the object. To her, these two ideas are antithetical and acceptance of one precludes acceptance of the other. If we see images then we don't see objects. She holds firmly to this viewpoint throughout the exchange.

> Hilary: If we see people as images, then if we looked at our own hand then they'd just be an image. You wouldn't see it because it would just be an image. I mean this hand touching this hand would be just an image, right?
>
> Researcher: No, your hand is actually touching your hand but you see it as an image.
>
> Hilary: No it's an image touching an image.
>
> Researcher: No, no. Mark?
>
> Mark: What you're saying is if I look at (inaudible) here, he would be there. It's just that I see him as an image. He would be there.

Hilary is raising the same point as Eleanor. Mark sums up the difference between images and objects in a concise manner.

> Hugh: Well you say with the image, you say that like with Hilary's hand, you see the hand as an image but it's not it's a real thing, an image of her hand.
>
> Researcher: Well in the sense that you couldn't stick her hand in your eye, could you? I mean if Hilary stuck her hand in your eye it wouldn't help you see it, would it? So you couldn't have her hand in your eye unless she poked you in the eye. You could only have an image of it.
>
> Hugh: It's not the real thing, it's an image.
>
> Researcher: An image is the way, we see images of real things. And that's how we see.
>
> Voice: It's confusing.

The last comment sums up the discussion well. It is confusing! In fact, the nature of the image is probably the most confusing aspect of the whole reflection theory of seeing and is the one which the students have the most difficulty in understanding.

The Nature of White Light

As part of their efforts to find out why objects appear coloured when we look at them, the students tried to think up ways to discover whether white light was pure and colourless or was made up of all colours.

> Donald: For white light is a combination of all colours you could take one of those rocks when you shine the light it has red, blue, and yellow on the other side and then that would prove colour, and then that would also prove white light is pure colour.

Donald thinks up an experiment to try to resolve the question of the nature of white light, that is, whether it is pure and colourless or whether it is made up of all colours.

> Monty: Well you get proof of white light is a combination of all colours by getting different colours of transparencies, sticking them together and shining a light through them.

Monty approaches the question from the other end. If white light is a combination of all colours, then all colours should combine to make white light.

The Colour of Objects Under Coloured Light

The experiments carried out by the students on why objects appear coloured mainly involved looking at different coloured objects under different coloured lights. The students observed that under coloured light, objects did not look the same as under white light. In the session where the researcher presented the reflection theory of colour, the students were asked at one point to read a handout (see Appendix E) which explained why.

Hilary: Well you said that, here it says that white light is all colours and you said if the white light went on to the red and if the green went on to the red object it would look black. If the white light is all colours then why doesn't it when it reflects off the red, why doesn't it show white because it's all colours?

Researcher: Sorry, run that by me again?

Hilary: Well you said that if the green light went on to the red light....

Researcher: On to a red object, yes....

Hilary: Then they would be black....

Researcher: It would look black.

Hilary: It would look black. And why does it because white light is all colours and why doesn't it reflect all colours, the object look black when we look at it under white light.

Researcher: Okay. The reason the red object will look black, black is the colour you get when all colours are absorbed. That's why when you wear a black shirt in the sun you get really hot because all the light goes into your shirt. None of it bounces off. White is the opposite. When you wear something white the light all bounces off so you feel cool. Now the reason it appears black, the reason a red object appearsblack in green light is because when the green light hits it, there's no red in that green to be reflected off to your eye. So when the white light hits it, the white light does have red in it, along with the all the other colours, and it's the one that bounces off and comes to your eye.

Hilary: Why doesn't, like, all the colours bounce off and why don't you see black?

> Researcher: Because those are the pigments in these objects. These pigments act in a way that they separate out the light. They take in certain colours and bounce off certain other colours. That's just the way they are.

The explanation for why the red object appears black under green light is long and complex. It involves the nature of white light, absorption and reflection, and the nature of pigments. It also involves dealing with a totally unfamiliar situation, that is, looking at coloured objects under monochromatic light. It is not something which can be assimilated in one sitting. However, an understanding of it leads to an understanding of the reflection theory of colour.

Why Are Certain Phenomena Certain Colours?

By the end of the sessions on colour the students were raising a number of questions about why certain phenomena were certain colours. These included "Why is the sky blue?", "Why is water blue?", "Why is space black?", Why is the sun yellow?" and, "If snow and clouds are made of water why are they white?" Two related questions which were asked were, "If black absorbs all colours, why can we see it, since we see objects because of the light which reflects off them?", and, "What would an object look like if it could neither absorb nor reflect light?" The fact that students asked these questions and wanted them answered indicates that they were both thinking seriously about the nature of seeing and colour and also that they felt that such questions are answerable through an understanding of how we see and why objects appear coloured. The nature of the questions also shows that students were thinking seriously about the science they were involved in. None of the questions are simple fact recall questions. All involve explaining why or else involve an application of a general theoretical knowledge to a specific example. Such questions can be an important source of data on what students are thinking and on what learning is taking place. At the beginning of the study the researcher asked most of the questions. The questions varied in complexity, that is, from simple recall to asking for conceptual explanations or asking for applications of general concepts. Soon students started asking questions, which, again, varied in complexity. These questions were at first usually answered by the researcher. Later some students began both asking high level questions, such as those mentioned above, and trying to answer them. This last situation was an indication that "good" learning was taking place.

After the questions mentioned above were asked, then, attempts were made to encourage the students to answer some of them. This was successful in some instances, although not in others. For example, a student was able to explain what an object would look like if it neither absorbed nor reflected light.

> Researcher: Donald's question was, if you want to think about it, what would happen if an object could neither absorb light nor reflect light? What would it look like? Yes?
>
> Voice: Black.
>
> Researcher: That's a possible answer. Yes?
>
> Eleanor: We wouldn't be able to see it.
>
> Researcher: And so what would be a good comparison, Eleanor? What is something that when you look at it you can't really see that it's there but it's there?
>
> Eleanor: Glass window.

Eleanor's answer requires a good grasp of the concepts of reflection and absorption and the application of those to an unusual situation. Her answer is scientifically correct.

Sometimes the questions asked by the students lead to answers which then lead to other questions. The question, "Why is the sun yellow?" was answered by the researcher in terms of the scattering of light in the sky, especially blue light, and how the subtraction of blue light left predominantly red and green which made yellow. This yellow was the yellow of the sun. When this answer was given, the student who had asked the original question immediately asked why the sun looked yellow from outer space. He had realized while listening to the explanation that in outer space there would be no atmosphere to scatter the light and thus the explanation would not apply. At this point the researcher asked the student to check his facts and to try to discover what colour the sun did look at it in outer space. The student felt this could be done by looking at photos of the sun taken from space. He was cautioned that these photos would have be taken from outside the spacecraft, and was asked why. The student answered that the spacecraft itself would have an atmosphere of some kind which might affect the results of the photos. The original question, then, lead to further exchanges, further questions, and further explanations. It also involved the student directly in finding out the answer to his own questions. In this manner the student became motivated to continue his learning outside the confines of the classroom and to take it in a direction of his own choosing.

DISCUSSIONS IN THE INTERVIEW GROUP: INDIVIDUAL CASE STUDIES

Shawn

Theories of Seeing:

The first instructional intervention was when the researcher presented the four theories of seeing (see Appendix D; see Appendix B, version 1). After the presentation, the class broke into small groups. The researcher went with the interview group of Shawn, Paul, Cari, Zelda, and Colleen, and and taped their comments.

Shawn is the first to offer his opinions in the small group.

> Shawn: Well I think the illumination theory is best. Say I'm in my room and the lights are off. You can't really see. And then I switch the light on right away and then you can see everything. Because if the sun shines on the tree and then the light rays would just go straight right here on your eyes and you could sort of see it, I guess.

The view Shawn is expressing here is the same as the view he expressed in his pre-evaluation, response journal, and interview.

After presenting his view, Shawn then participates in a group discussion aimed at clarifying where the light from the sun is going in the diagrams of the theories of seeing which the researcher put up on the blackboard for reference. It soon becomes clear from the comments of Shawn and the others that the diagrams are misleading the students because they seem to show light from the sun shining only on the tree and not on the observer. The diagrams are changed by the researcher (see Appendix B, version 2). Students in other groups revealed by their comments, "That's better!", etc., that they were also confused.

Shawn now states that he supports the visual rays theory. However, it is clear from what he says that his basic ideas have not changed from before, only the labels he puts on them.

> Shawn: Well now I think it's the visual rays one because I think that the sun's rays would go down everywhere and on the tree and the tree with the rays would reflect on your eyes and also the sun, the sun's rays go down on you would reflect off too. And then you would see the tree.

Again, Shawn is separating seeing from the reflected image. The reflected light is not the image but illumination of the object. For Shawn, seeing is a separate act directed toward the tree.

The group then becomes involved in a discussion of how the sunlight reaches the eyes of the observer. Shawn expresses his confusion in a brief exchange with the researcher.

> Shawn: And I don't see how the rays got into the visual rays' (sic) eyes.
>
> Researcher: Which rays, you mean the rays from the tree or the rays from the eyes?
>
> Shawn: The sun's rays. I don't see how they got into your eyes so you can see. If there's no light you can't see.

It appears that the thrust of Shawn's remarks is in reference to an "act of seeing". He is wondering how the light can enter the eye if the observer does not direct his eye in some way toward the object. When Shawn drew rays from the eye to the object on his pre-evaluation, then, on the one hand, he may have meant some type of actual motion outward from the eye to the object. On the other hand, he may have meant merely that the eye must be facing in a direction where it can receive the reflected image of the object.

Shawn makes one last contribution before the class reconvenes as a whole, by raising an objection to the reflection theory.

> Shawn: You'd get pretty sore eyes if the rays went on your eyes all the time....Your eyes would get pretty red if you were doing the two way. It would be like looking into the sun.

Shawn now uses this point as further support for the visual rays theory.

> Shawn: Actually the visual rays, it doesn't get in your eyes. I like the visual rays one now that you think of it. Now I don't see how you could see in the illumination one.

After the class reconvenes, Shawn makes no more comments. His journal entry after this session about how we see objects shows minimal change: "The sun shines all around and then rebounds off the object and into your eyes and then back and fourth (sic)". When compared with his first entry, the differences are the extension of the sun to shining "all around" rather than "on the object"; the change from "onto your eyes" to "into your eyes"; and the replacement of "and then you see the object" by "back and fourth (sic)". The first change may reflect the change made in the diagram, the second may refer to the discussion about the "screen in the eye", and the third may be an attempt to clarify what he means by the "view of the object", a point brought up in the discussion that day.

Evidence For Theories of Seeing

The second instructional intervention involved attempts by the students to present arguments or experimental evidence in their small groups to support their particular theory of how we see objects (see Appendix D).

Shawn's first remarks in the small group concern the ability to "see darkness".

> Shawn: Today I was in my bathroom and I stuck a towel under the door of the crack and the whole bathroom was black, right? Say that the room is as black as that blackboard, you can see the blackness. You can see the

darkness and there's no light. If the light in the whole school went off you could without....

It seems that here Shawn is trying to make a case for seeing without light. He has tried an experiment at home to support his viewpoint.

After some comments from the other members of the group about blackness, Shawn suddenly declares that he "thinks it's reflection". He uses the overhead projector as an analogy to explain his thinking:

> Shawn: Now say that thing was on, that overhead is on. The light from the bottom goes up, hits a mirror that's right like that, hits that, and goes on the screen, right? And then so I think that's how it works only downwards and the light hits the tree and our eyes and goes that way and not up and then that way.

Another student expresses confusion about what he is saying so he continues.

> Shawn: Say this overhead is on. Then there's this little thing right in here and it hits right in here and goes up.
>
> Researcher: There's a mirror in there.
>
> Shawn: And then the light reflects off it. I think that the light from there hits our eyes and goes that way and goes not up but down.

Here there is an objection from a student that our eyes are not mirrors.

> Shawn: Not mirrors, but rays will reflect on it though and back down.
>
> Researcher: So can you give me the order in which this happens?
>
> Shawn: Okay. The light goes down on the object and hits your eyes and goes that way on the object that you're looking at. And that's the same as that, only the light from there is from down up and that's from up down.
>
> Researcher: So the light comes to your eyes and then to the object. That's sort of a backwards reflection theory.

> Shawn: Yeah.
>
> Researcher: Because the reflection theory is that the light goes to the object and then to your eyes. So you're saying the light comes to your eyes and then goes to the object.
>
> Shawn: Mmmhmm.

Again, this dialogue shows that Shawn basically still holds the same view of how we see. At times he gives it different labels but its essence remains the same.

After some other students have expressed their views, Shawn presents a new synthesis.

> Shawn: I also think that it's part, some, not half, but some of illumination as well as reflection.
>
> Researcher: What purpose would the illumination serve?
>
> Shawn: When it's dark and you turn on the lights and then right away the reflection theory sort of starts because all the rays bounce off and off so fast and then we can see. And then so that would be sort of like illumination as well because then there's no light. Switch on the light and then the rays are bouncing and bouncing like really really really fast until you can see.

Again, Shawn presents the idea that light reflects but, for him, light reflects to illuminate the object and not as an image of the object.

Later, the researcher suggests the students consider the role of the eye in seeing, since the conversation has so far centred on light and the object. Again, Shawn is first to present his ideas.

> Shawn: Well, when you look at the sun, say, if you looked at it then something, the cells in your eyes sort of like die. So when you look at a

> normal light bulb nothing will happen. That would prove that something in your eye....
>
> Researcher: What would be the difference between a normal light bulb and the sun?
>
> Shawn: The sun has more power. A light bulb is just certain watts so....

Shawn is beginning to think about the effect of light on the eye and perhaps what implications that has for the roles played by the light and the eye in seeing.

Another student then volunteers that there is a screen at the back of the eye and that everything reflects off it. Shawn picks up on this, becoming quite enthusiastic about his new thoughts, and works it into his previous conception.

> Shawn: Well maybe that screen, that light would go in and the screen....Okay, when there's no light the screen of your eyes would be just all black and then when the light goes in....Hey this is a good idea....Okay, when there's no light, you can't see anything because maybe there's no light in the screen of your eye and then when you're looking at something the light goes in the screen of your eye and then the screen sort of opens up and you can see the object.

When probed for an analogy, Shawn replies.

> Shawn: Our eye is like a camera and when there's no light or film in it the camera won't work or the screen won't work and then when there's film in it or light in it you can see and you can make the object out when there's light in it.

Again, he adds more detail to his already held theory.

Finally, at the end of the session, Shawn draws an interesting conclusion about how we see.

> Shawn: Now I think that it's some of all of it now because there's reflection and then there's two way and there's illumination.

In other words, Shawn feels that a combination of all four theories gives the best explanation of how we see.

> Researcher: If we go with two way then we have to think what is it in our eye that sends something out because you're saying that something comes out from our eye, sort of, we look. What is coming out from our eye and what is it in our eye that sends it out?
>
> Shawn: The view of the object. The light goes in and the two way would be the light going in and viewing it and then something, yeah, I don't know, maybe.

Shawn is still working out his ideas.

Shawn's journal entry presents a summary of some of the new ideas he has put forth during the session: "I think that it is all of them. I think that our eyes are a camera and the rays go in your eyes and goes (sic) on a screen and then you see the object."

Reflection Theory of Seeing

After the researcher presented the reflection theory of seeing (see Appendix D), there was a class discussion. Shawn did not contribute to this discussion.

Shawn's journal entry after this presentation and discussion is quite different from his previous entries. He writes: "I think that it is reflection because the sun goes on the object and then into your eyes and on a screen. The screen then makes out an image of the object and then we see it." This entry may express a new understanding of how we see or it may just be a copying down of rote ideas presented by the researcher. Significant additions are the reference to the screen in the eye, that is, the retina, and the use of the word "image". The grasp of the concept of the light image is crucial to a scientific understanding of how we see. Shawn seems aware of this concept. He also has connected the retinal screen with the image, that is, he postulates the retina as the place where the image falls.

Theories of Colour

The researcher presented the two theories of colour to the class as he had presented the four theories of seeing (see Appendix D). The class then broke into the small groups.

In the following small group session, Shawn offer his views first.

> Shawn: It's not the object one. Here's my theory of why, okay? I think it's the light one and I think it's this one right here, the cells thing, because I think that there's special cells in your eyes and then the light....Like, say I was looking at my hand. The light goes off my hand and on the screen of my eye, and then my cells make it look, and then they make it look the way it should be, and I see it.

Here Shawn focusses on the nature of the eye. He tries to develop the idea of cells in the eye which detect colour, relating them to the previous idea of the "screen" in the eye. At the same time, he again affirms the importance of reflection in seeing, stating that the light reflected from the object travels to the eye. However, he makes no specific mention here of any "image".

Shawn next makes a brief foray into the question of whether or not certain animals see only black and white. This results from his suggestion to dissect an eye to find the colour-sensitive cells.

> Shawn: (inaudible) pop it back in.
>
> Researcher: Sorry, we can't dissect anybody's eye today.
>
> Shawn: Well if you got a frog's eye.

Researcher: But that would be assuming frogs could see colour and we don't know that.

Shawn: You said dogs see black and white, right?

Researcher: That's assuming we know that.

Shawn: But maybe we could make up an experiment like that. Because they see black and white, how come, well probably they wouldn't know hardly where to go. Oh well, that's weird cause say dogs see black and white and then how come some of a dog's eye can see in the dark and we can't?

Shawn obviously feels that the ability to perceive colour is an important aspect of seeing as a whole. He thinks that the dog will have trouble seeing in general, that is, "they wouldn't hardly know where to go", because the dog sees only black and white.

The conversation now turns toward what will happen if coloured lights are shone on different coloured objects.

Shawn: Then they'd probably turn out the colour of the light you shine.

After interjections by three other students, Shawn explains how he thinks this could be verified experimentally.

Shawn: Well you know what you could do is have one blue chalk, one green chalk and one red, and then have all the same lights shine on them. I mean well....

Shawn has a good understanding of how to set up this experiment by keeping one variable, the light colour, constant, while changing the other variable, the chalk colour.

Another student says that all other light except the coloured light must be excluded from the room to make the experiment valid. The storage room is offered as a place which can be made "totally" dark. Shawn suggests that equipment from the *Optics* kit be used to provide the coloured light in the dark room. He is obviously working out ways of actually carrying out the experiment in practice.

Shawn joins the other members of the group in predicting what will happen when certain colours of lights are shone on certain colours of objects. He agrees with the rest that when a red light is shone on a red object, the object will appear red. He predicts that when a red light is shone on a green object, the object will appear "orangey", then adds, "or whatever those colours make." In other words, Shawn thinks that the colour of the light will mix with the colour of the pigment to produce some sort of intermediate combination.

(There is a break here of undetermined length. It was discovered the tape had ended and so a new tape was put in.)

Shawn starts off the new taping by making some new predictions about light and colour.

> Shawn: Just let me start again eh? You two said that if we were in a dark room and had a flashlight and say a green thing over it and shined it and it went through and then there was new light and it shined on a solid red thing that you would think that it would change to orange or like that, right? And I think that if the solid object is all red, pure red, and when you shine it on it that the red, the object will change. And so I think that if you shine red light on the whole room that (inaudible) right there will stay red and won't change.

Shawn now disagrees that the light and colour will "mix"and instead proposes that the colour in the light will dominate, that is, if red light is shone on an object, that object, no matter what colour it appeared in white light, will appear red, that is: "I think that if you shine red light on the whole room that (inaudible) right there will stay red and won't change."

Shawn then disagrees directly with another student who reproposes the "mixing" theory by drawing an analogy with paints.

> Shawn: See I don't think that that's the same 'cause look. Right, if we turned off all the lights in the whole school and we turned on red lights, right? Say there were red lights like there. Then would you think that that would change orange, that would change blue, that would change greenish?

Shawn, then, seems now to have settled on a view which makes the colour of the light the determining factor in what colour objects will appear. He has discarded the "mixing" theory completely at this point.

In his journal, after the class ends, Shawn makes his first new entry about colour. He writes: "I think that there are special cells in our eyes that make up the object and then reflects off our eyes and on the object." Here Shawn combines his previous theory of seeing with his new idea about special cells in the eyes. He is attempting to integrate the phenomenon of colour into his general theory of seeing.

Evidence for Theories of Colour

The stated purpose of this whole session was to try to discover why objects appear coloured. After a brief introduction about the materials, the students broke into groups to try their experiments.

Shawn's group experimented with different coloured paper squares and different coloured lights. The members were to predict what colours would result from various combinations of coloured squares and coloured lights. Scott's voice is first: "Yeah, I was right." Others disagree with his perception of the resulting colour. More combinations are tried. Shawn comments, "Hey, I made pink." There is a pause while the cord to the light box is plugged in again.

Shawn presents his theory of colour again, one similar to that outlined in his journal after the previous session.

> Shawn: Well I think I know how we see like green and blue and red. Say I was looking at this flashlight. The light (inaudible) down on the flashlight, right, and say there was light in the room, and say this flashlight was red. And then the light would go in our eyes and on our screen and the screen has special cells that make up the object. And then the cells in our eyes make up what the object looks like. And then you see the real shape of the object. So that is my theoretically awesome theory.

As can be seen, he is still fascinated with the aspect of seeing involving the eyes, especially the "special cells".

The members of the group again return to their experiments with combinations of coloured squares and coloured light. A pattern of disagreement emerges involving perceptions of the appearance of the squares under different coloured lights. Shawn disagrees with one student who proposes that she perceives green: "No, it's dark, dark yellow." Later, he disagrees vehemently that dark-green is being perceived: "Black, it's black, it's black." This disagreement continues with no resolution.

At this point Shawn decides on a way to resolve the disagreement, that is, an appeal to "expert" authority of the researcher.

> Shawn: So you're the one that has to decide.

Shawn clearly means that the researcher must decide whether dark green is being perceived or black. The researcher refuses to resolve the disagreement, declaring that science and what happens in the world is the authority, not the researcher.

Further disagreements along the same lines ensue after the researcher leaves the group. Shawn suggests that one of the students who disagrees with him must be colorblind. It is clear Shawn is now trying another method of resolving the disagreement, that is, calling into question the physical ability of perception of the members who oppose him. But the student he is challenging merely turns the tables by suggesting that he is the one who is colourblind. She appeals to the expert authority of her eye doctor who recently examined her. Shawn says that the eye doctor must be wrong. Then he suggests that the other person in the group who agrees with the same girl must also be colourblind. This impasse continues until the researcher returns.

The students in the group are shown a mini-demonstration by the researcher. The flashlight beam is shone through three coloured filters laid on top of each other and white light is seen on the other side of the filters[†]. After the demonstration unidentified voices make various comments to the effect that, "It's white", "White is all colours", "They make white", "White is all colours, that explains it", "White makes all colours". Shawn may be one of these voices. Certainly he is involved at this point in observing the demonstration.

[†] This demonstration was erroneously conceived by the researcher. Although the light does appear white after passing through the filters this is not due to the filters "adding" their colours together. The researcher unwittingly designed the demonstration in terms of his own spontaneous conceptions about light even though he had spent time preparing himself for the science of the study. This error by the researcher further highlights the need for teaching for understanding rather than memorization since teachers may also make such mistakes.

Following this there are further experiments by the group members with coloured squares and coloured lights. Again there is disagreement over perception of the resulting colours.

Shawn then repeats the researcher's demonstration with the three filters.

> Shawn: Hey, look. Blue, green, and red, right? Right? Now watch. Looks so weird, eh, white.

Shawn has duplicated the researcher's experiment. He expresses his amazement at the results to the researcher who has just returned to the group.

> Shawn: This is so weird. I just think it's so weird how when you have all these and it's green and stuff, when you look through it like that it's white. I mean that's....

The researcher repeats the demonstration again. Shawn continues to be amazed.

> Shawn: I mean it's so weird. How can it be though?

Shawn is going through some type of cognitive dissonance here. The result of the experiment does not fit with his present understanding and he is trying to come to grips with it.

The researcher mentions the rainbow as an example of white light being broken into its colours. Shawn notes that after rain there are particles in the air. The researcher points out that these particles act like little prisms and break up the white light. Shawn sums up what he has learned for himself and the group: "So, like, if you take all the colours and you put them together they're white."

Shawn's journal entry after this session is the same for both questions: "My ideas have not changed." If he has learned something new about the nature of white light, he cannot or will not apply it at this time to his notion of how we see colours.

Reflection Theory of Colour

In this whole class session, the researcher presented the reflection theory of colour to the class (see Appendix D). There was a discussion during and after the presentation but Shawn took no part in it.

Shawn's journal entry after this session again declares that his ideas have not changed. He is retaining his previous conception even after the presentation of conflicting evidence by the researcher.

Paul's Ideas During Intervention

Theories of Seeing

The first instructional intervention was when the researcher presented the four theories of seeing (see Appendix D). After the presentation, the class broke into small groups.

Paul's first statement during the small group discussion of the different theories of seeing tells which theory he prefers and why.

> Paul: I like the one that's illumination because you can't see without light, so when you turn them on you can see everything.
>
> Another student: Well, I've changed my mind. I think it's the reflection okay? Because if the sun shines on the tree and then the light rays would just go straight right here on your eyes and sort of back and then you could sort of see it, I guess.
>
> Second student: I'm going with Colleen. I like the illumination.
>
> Researcher: So why do you like it?
>
> Paul: Cause if you had no light, you couldn't see anything.

These statements of theoretical preference are consistent with Paul's previous views, that is, that light illuminates objects so we can see them.

Later on, Paul criticizes the visual rays theory.

> Paul: Well, the visual rays one. I don't think the light just gets to your eyes. That one's wrong because the sun's right here and....
>
> Another student: (inaudible) the tree?
>
> Paul: Yeah, then say there was one tree right here. The sun would have to shine on the tree and the ground and you too, not like straight on the tree only.
>
> (Comment by another student)
>
> Paul: Yeah because the light right here shines all around and not on, right on my shoe.

But these comments make it clear that his criticism is based on the misleading way in which the researcher has drawn three of the diagrams (see Appendix B, version 1), that is, with the light from the sun shining on the tree and not on the observer.

Finally, he sums up the theory he prefers, while at the same time criticizing the reflection theory which another student has just spoken in favour of.

> Paul: The illumination one, it would shine all over. Cause if the sun shoots it onto the tree and it comes back to your eyes, I don't see the way that works. With the illumination, it's going all over.

Again the reference is to the misleading way the diagrams have been drawn by the researcher.

After the diagrams are altered so that the sun's rays are shown dispersing over the whole picture (see Appendix B, version 2), Paul expresses confusion.

> Paul: Now which one am I going to pick? They all look the same

almost.

In response to another student, Paul wonders at how the light can be reflected to the observer's eyes so quickly.

Paul: Well, I just don't know how it gets to your eyes so fast like that.

Researcher: Do we know anything about the speed of light?

Paul: Like really, really, really fast.

Possibly this answer satisfies Paul because he does not raise any more questions on this topic.

Later on, Paul raises a concern about light reaching the eye.

> Paul: I'm not sure how if I was standing right here and the sun was up here, and if you were standing here how the rays would shine down on the tree and then hit something and go straight in like that. How can the sun know that you're standing there and the rays go straight in your eyes? They might not always go straight in.

Here Paul makes the rays "active" and the eye "passive". The rays must "seek and find" the eye. The issue being raised here is how the eye focusses. It is possible that it is this question of focussing which leads to the conception of visual rays, that is, if the eye focusses and thus plays an active role in seeing, then the eye "looks at" something. This "looking at" something, then, involves something "going out" from the eye to the object.

After the researcher leaves the group, Paul, with the other members of the group, explores the question of seeing when in shadows. Paul is one who is puzzled about this.

> Paul: This is weird, though. Say you're under a tree and there's a shadow, right? Shadow all around the tree and you're sitting right against the stump. How can you still see the tree then?

The reasoning goes, then, that if seeing is by reflected light and the observer is in the shadow of the tree, then the fact he is in shadow means that no light, reflected or otherwise, is reaching him and so he should not be able to see the tree.

The ongoing discussion of the question of the observer in the shadow continues and Paul listens for awhile. But he soon shows he is still wondering about the observer in shadow.

> Paul: I don't understand how when there's a shadow around a tree and you can still see the tree stump.

The idea that the shadow may be caused by the blocking of one set of light rays and the image by another, does not seem to occur to Paul or to the other students.

After this, the whole class reconvenes. During the whole class discussion, Paul demonstrates he is paying attention but is confused. After two students propose ways of combining the two-way and the reflection theories, Paul interjects.

> Paul: I still don't see how you can mix the two-way and the reflection.

When asked why he objects to the combination, he says:

> Paul: Well, I don't have an objection. I just don't see anything. I don'tsee what's going on.

In his journal, Paul first says he wants to make one addition to his thinking about how we see objects. "My ideas are the same except for one thing. The light shines down on the black writing and that's how you can see the writing. That goes for everything." When compared with his initial entry, the change in his thinking seems to be that he is now saying the light actually shines on the object rather than just is "there" in the room. He is trying to be more specific about the action of the light. Paul also makes a new journal entry about how we see colour. At first he writes, "Same feelings". Then he adds: "You need rays to see objects and you need rays to see colour." It is not clear whether the "rays" he is referring to are light rays or visual rays but, again, he is clearly going beyond his preliminary belief in simple illumination and is trying to build a more comprehensive understanding of how we see objects and why they appear coloured.

Evidence for Theories of Seeing

The second instructional intervention involved attempts by the students to present arguments or experimental evidence in their small groups to support their particular theory of how we see objects (see Appendix D). After the group comes together, Paul is not clear on what the task is.

Paul: What are we supposed to find out here?

Researcher: What do you mean, what are you supposed to find out?

Another student: Try to prove something.

Paul: How we see?

Researcher: Yes, we're still working on that same question.

Paul asks no more questions about what to do.

During the investigation, Paul makes brief comments. At one point he notes that light is "coming in (to the classroom) through those classrooms." Further on he makes an observation about something he is trying with the equipment: "Hey, this is neat. Is this black construction paper? Cause when you shine it off the mirror it kind of looks gray." Paul is commenting peripherally on issues and is not at this time making any statements about the overall question of how we see.

Paul re-enters the discussion when the question is again brought up as to how the observer is able to see when he is in shadow.

> Researcher: Okay, let's say we're outside and we're standing in the shadow of a tree and sun is our only light source.
>
> Paul: Maybe it reflects off the wall behind us.

Here Paul is beginning to think about light coming from different directions because of reflection.

At the same time, Paul is still thinking about the observer in the shade.

> Paul: You can't see the rays in the shade then.

The question of the observer in the shade, then, is still on Peter's mind and he has not yet resolved it to his satisfaction.

Near the end of the discussion, however, Paul comes to a startling synthesis.

> Paul: I think it's reflection. I don't know why. If it didn't reflect off the object, you wouldn't be able to see the object. If you were in the shade, some rays hit the tree to make the shade and the other rays come back so you can see the tree.

It is possible that Paul's opting for reflection may have been influenced to some extent by his relations with Shawn. However, his statement here still shows that he has definitely been working out some of the problems raised in the group and has been trying to understand their implications for the overall theory. His thinking is changing.

Later, during a discussion of how light travels, Paul shows he is clear on what happens to light when it hits a mirror: "It bounces off", and when it hits a transparent surface: "But if it's like glass or something it goes straight through." He also draws the attention of the group to the reflection effect from a piece of paper: "See, light reflects off this paper."

Paul's final comment during this session comes when the group is talking about how the lens of the eye functions. Paul describes how he thinks the lens works.

> Paul: Cause when you can hardly see it you open wide and you can see things more clearly. And then when you close it you can't see anything.

Although Paul is perhaps confusing the lens with the pupil, he is now thinking about the role the eye might play when we see objects. He is going beyond the role of light and is looking at the other factors involved.

Paul's journal entry shows he has clarified the question of the observer in the shadow. He writes: "When your (sic) standing in the shade, some of the rays hit the object, some of the other rays deflected of (sic) a wall, come from behind, hit the tree. So I go with deflection." He has also extended this clarification to the idea of how we see. By "deflection", he presumably means "reflection". It is not clear how he conceives of reflection, but he is certainly thinking about it in terms of how we see.

Reflection Theory of Seeing

During the whole class discussion after the researcher presents the reflection theory of seeing (see Appendix D), Paul makes only one comment. This is during an exchange about "images", after several students have suggested that if we see images of objects then we do not see objects at all. That is, the objects are "not really there at all."

> Paul: Well, I was wondering, you're seeing the actual image. Oh well. An image could try and kill you and you wouldn't worry because it's only an image.

Paul is taking an extreme example to make his point. He is confused about the nature of images and their relationship to actual objects.

Paul's entry after this session is to the point: "No comments, you covered it all Mr. MacDonald." Unfortunately he does not write down any summary of his ideas. He also notes, "I'm sick but nothing else", indicating that he is not feeling well that particular day.

Theories of Colour

The researcher presented the two theories of colour to the class as he had presented the four theories of seeing (see Appendix D). The class then broke into the small groups. Paul's small group is well into the discussion before he makes his first contribution.

The students are discussing with the researcher the conditions and materials necessary for carrying out experiments with coloured light. Paul interjects that an overhead projector might be useful: "Why not just use an overhead and it shines through it?"

A little later Paul makes his only other contribution for the session and tells how he thinks objects appear coloured.

> Paul: I think well maybe (inaudible) the object absorbs the colours out of white light and reflects others because assuming that light is a whole bunch of colours and actually you need some, no you can't do that. It would be kind of hard to do an experiment on that. But I was thinking that whatever colours that are in the light, some of them stay in the book and some other ones come out, and that forms the colour that you can see.

Still waters run deep! Paul remains silent for most of the discussion then puts forth a precise scientific explanation of why objects appear coloured, complete with reference to absorption and reflection!

At this point in Paul's journal there is a problem in matching his comments with the sessions. This is because he has only two more journal entries, both undated, while there are three sessions including the one just completed. The last journal entry is clearly from the final lesson because it includes a farewell. The other entry is, "no changes", which could apply either to this session or to the next. In any event, it is unfortunate that Paul has not written down any of what would appear to be his new ideas for this session.

Evidence for Theories of Colour

The stated purpose of this whole session was to try to discover why objects appear coloured. After a brief introduction about the materials, the students broke into groups to try their experiments.

Paul's group experimented with different coloured paper squares and different coloured lights. The members were to predict what colours would result from various combinations of coloured squares and coloured lights.

Paul is participating with the others in predicting what colour will appear when different coloured lights are shone on various colours of construction paper. He comments, "I'm righter than you are", to another student. After someone suggests he isn't right, he just says, "Fine."

Then Paul tries to explain what is happening in an experiment he is engaged in.

> Paul: See, look. They're sort of white now, right? And when it's half and half the blue and the red (inaudible) red's darker. That looks like orange now. That looks like orange. And that's lighter and that's light and that's (inaudible). So that means that nothing happens.
>
> Researcher: What are you discovering?
>
> (There is a pause while the cord is fixed)
>
> Paul: The light goes through it, makes the colour....
>
> Researcher: Light goes through what?

> Paul: Light goes through the little pieces of colour and if you have a lot of colours then it blends and makes the colour on the other side. The light changes colours as it goes through. Like say you just have blue there....
>
> (There is another interruption while the cord is fixed. Paul does not continue because another student starts speaking.)

This is a bit difficult to follow. However, Paul is trying to explain what happens to the light when it passes through a combination of two or more filters of different colours. Unfortunately, he does not get a chance to really explain what he thinks because of the interruptions and then the new speaker.

Later, there is a discussion about what happens to the white light at the red filter so that it appears red on the other side. After a student says that the red filter adds red to the white light, the researcher suggests that there may be another possible explanation: "So the possibility is either that the red adds red to the white light or what else?" Paul shows his involvement by chiming in: "Or takes it away." Again, he does not get a chance to complete this thought because it is completed by another student, but he is party to the discussion and no doubt hears the other students' scientifically correct summation.

Paul is then involved in a controversy in the group over what colours are being seen when certain filters are used with certain coloured squares. For one combination, Paul and another student assert that the colour seen is "black", while the three other students in the group just as firmly assert that the colour is "dark-green". There is obviously a difference in subjective perceptions. Interestingly, this split is along gender lines. Paul takes the normal route of appealing to adult or teacher authority, and appeals to the researcher to resolve the controversy: "You're the one that matters". However, the researcher refuses to sort things out. The controversy continues (see page 157). However, in this discussion Paul also disagrees even with his ally about another apparent colour. His ally suggests purple, one of his opponents suggests blue, and Paul compromises with, "It's in-between, bluey-purple." Paul presents his own view, even though he is the only one who holds it.

The researcher returns and does a brief demonstration to show the composition of white light. He shows how three different coloured filters can be combined to make the white light of the flashlight remain white on the other side of the filters. After the demonstration and a number of comments, Paul interjects: "Why are we doing this experiment?" Paul obviously does not see the significance of the experiment which is that white light can be made up of certain colour combinations. To his credit, however, he once again demonstrates that he is not afraid to let everyone know when he does not understand something.

Later, Paul is puzzled again, this time about the difference between combining colours of pigments and combining colours of light.

> Researcher: But it only works with light, if you put all colours of light together.
>
> Paul: That's confusing.
>
> Another student: No, if you took like colours and (inaudible) they wouldn't turn out white.
>
> Paul: I know, but it's just if you can shine something through.

Paul is making an acute observation here. He is saying that the filters themselves will not appear white as a group when someone looks at them. They only recombine the light so that the light looks white. Without knowing it, he is drawing a scientific distinction between the behaviour of pigments and the behaviour of light.

As previously pointed out, Paul's entry in his response journal, if it is for this session, merely states: "No changes."

Reflection Theory of Colour

During this whole class session, the researcher presented the reflection theory of colour (see Appendix D). Paul did not say anything.

Paul's final journal entry, after this session, is as follows: "You've covered it all but now I've learned much more about how we see. You've been a great teacher. Chow! I don't believe that there are 10,000 shades of colour that our eyes can see. That's the end of Riples (sic) Believe it or Not." Although Paul does not outline his ideas at this point, from his perceptive insights during the interventions and his demonstrated attitude of not accepting what he doesn't understand or agree with (even to the end!), it seems his statement that he has "learned much more about how we see" should be taken at face value at this point.

Cari's Ideas During Intervention

Theories of Seeing

In the small group, Cari first expresses her preference for one of the four theories presented.

Voice: What one do you like Cari?

Cari: The two way.

Voice: Why?

Cari: Because you see things when there's light shining.

Cari is combining what she feels are the two components of seeing, the eyes, that is, "you see things", and light, that is, "when there's light shining.

Further on, Cari expresses a new preference.

> Cari: I like the illumination one.
>
> Researcher: Why?
>
> Cari: Because the sun gets to whatever you're looking at and everything else and your eyes, and it doesn't just go to one thing.
>
> (Other students and the researcher make various comments)
>
> Cari: It wouldn't only go on the tree that you're looking at.

Here Cari is getting involved in the confusion about how the diagrams were drawn. As originally drawn, the illumination diagram was the only one which showed the sun's light shining "all over". The other three diagrams created the impression that the sun was only shining on the tree and not on the observer (see Appendix B, version 1). The diagrams were changed at this point to show the light in all three shining "all over" (see Appendix B, version 2).

Soon Cari raises an interesting point which seems to her to be a contradiction.

> Cari: If the light reflected off the tree, it would have no shadow. And like when you have a mirror it'll reflect off and, like, if you have black it probably wouldn't reflect off the tree unless the tree is made out of a mirror.
>
> Researcher: Are reflections and shadows different things or the same things?
>
> Cari: Different, because if it would reflect off, if there were two trees here then the reflection of this one would light up this one, or the other way around.

Cari is suggesting a connection between light reflecting off the tree and whether or not the tree casts a shadow. She feels that the fact that the tree casts a shadow, which she has often observed as part of her own experience, indicates that there could be no light reflecting off the tree. She is not considering that there are multiple sources of light and that light rays are reflecting in all directions.

Cari raises this point again after the researcher leaves the group.

> Cari: There can't be light going into your eyes because you're in the shadow.

Again, she is presenting this as an argument against the reflection theory of seeing.

After the whole class has reconvened, Cari makes a contribution regarding the nature of the eyes of some night-hunting animals.

> Researcher: What about animals that hunt at night? What do you notice about their eyes? Cari?
>
> Cari: Really big.
>
> Researcher: Really big. So what might you think might be an explanation for that? Cari?
>
> Cari: So they can see in the dark.
>
> Researcher: And how would having a big eye help you see in the dark?
>
> Cari: To attract more light.

Cari has no trouble following the line of reasoning here and comes to a conclusion which potentially contradicts the view she expressed previously in the shadow-reflection discussion, that is, that seeing objects has nothing to do with reflection of a light image to the eye.

In her journal, in answer to the question, "How does light help us to see objects?", Cari writes: "Light shines on the object". In answer to the question, "Why do objects appear coloured when we look at them?", she writes, "Cause the light reflects the colours." These answers are almost identical to the ones in her first entry.

Evidence For Theories of Seeing

After the introductory remarks by the researcher (see Appendix D) and the students break into their small groups, Cari's first comment is again about the shadow-reflection question.

> Cari: Okay, but if you were standing right here and you're in the shadow, then there's no light to....
>
> Another student: If I was sitting this way and looking this way I could still see you.
>
> Cari: But how would the light reflect off your eyes? (She repeats this a little later.)

Cari is still wrestling with this apparent contradiction.

Later on, while another student is giving his ideas, Cari objects to the idea that blind people cannot see.

> Cari: If you're blind you can still see black.
>
> Voices: Yeah. No.
>
> Cari: You can see images when you're blind.

Either Cari is trying to make a case that light is not always necessary for seeing, or she is playing a bit of "devil's advocate" here while assessing the other student's argument.

During the same student's presentation, which involves an analogy between how we see and the way an overhead projector works, Cari raises another objection.

> Another student: And then the light reflects off it (the mirror in the projector). I think that the light hits our eyes and goes that way and goes not up but down.
>
> Cari: But our eyes aren't mirrors.

Cari quickly picks out a flaw in the analogy which weakens the argument being presented.

The reflection-shadow question is still bothering her, as she reveals further on in a long exchange.

> Cari: Yeah, but if you're standing in the shadow where would the light come from? You're standing in a shadow but you can still see everything around, then where is the light coming from? The light which is coming to your eyes, then there wouldn't be a shadow there. They'd be going all over. Shadow.
>
> Researcher: We could be in shadow, say from one light source, but possibly we could see by the light from another light source.
>
> Cari: Yeah but then if it reflected off, like, the light came to your eyes, then, like, then it would rebound off everything and it would light up where you're standing.
>
> Researcher: Okay. Let's say we're outside and we're standing in the shadow of a tree and the sun is our only light source.
>
> Another student: Maybe it reflects off the wall behind us.
>
> Researcher: Ah. So the light from the sun goes in other directions and reflects from other directions.
>
> Cari: But then there wouldn't be shadows.
>
> Another student: You can't see the rays in the shade then.
>
> Researcher: So what he's saying is there is one group of rays which is coming down and which is being blocked by the tree and which is causing the shadow, but there are other rays which are passing the tree, reflecting off things, and coming back and creating light by which you can see.
>
> Cari: But what would it reflect off?

Researcher: The ground maybe. An object. A wall.

Cari holds her ground and continues to question closely. She is not ready to accept an explanation or part of an explanation which she feels is unsatisfactory.

Later, Cari is asked again what theory she prefers and she expresses agreement with what Zelda has just said.

Researcher: Okay. What do you think, Cari?

Cari: I agree (that light reflects off objects).

Then she hedges.

Another student: Do you think it's some of illumination or....

Cari: Maybe, like, a little bit maybe. Kind of like combined (illumination and reflection).

Cari is still working out her ideas.

Finally, near the end of the discussion, another students suggests that there is a "screen" in the eye (the retina).

Cari: I agree.

Researcher: You agree what?

Cari: Your eye has a kind of screen in it and then like a camera.

Researcher: And which theory would this lead you to as being the most useful one? Or you don't think it actually leads to one theory yet?

Cari: Probably reflection.

Cari's ideas seem to have changed somewhat and she seems to be giving serious consideration to the reflection theory.

Cari's journal entry indicates some new thoughts. In answer to the question, "How does light help us to see objects?", she writes, "I think it is reflection. Cause your eyes are like cameras your eyes reflect the light." Her acknowledgement of reflection is a change from her previous adherence to illumination. There is no mention of an image but she is also applying a camera analogy. Finally, she seems now to agree that the eyes reflect light, even though she disagreed during the discussion, that is, "But your eyes aren't mirrors." One interpretation of this last statement is that she means that "your eyes receive reflected light". Another possibility is that she means that light reflects off your eyes "out to the object", that is, that she is now thinking about some type of visual rays theory, at least in part.

In answer to the question, "Why do objects appear coloured when we look at them?", Cari writes, "We can see colours cause dark colours attract more sun than light colours." She also draws a diagram like the one on the second question of the pre-evaluation, showing the sun, the tree, and the observer, but also including a wall behind the tree (see diagram). On her diagram, she draws rays of light from the sun reflecting off the wall and writes, between the tree and the wall, "No shadow". She also draws a ray traveling from the sun to the tree and then to the observer's eye. Her answer is a combination of a better understanding of colour, that is, "dark colours attract more sun than light colours", and also what appears to be a resolution of the question she has continued to pursue concerning reflection and shadow.

Reflection Theory of Seeing

(See Appendix D for researcher's introduction.) Cari does not contribute to this whole class discussion. Her journal entry states that, for both questions, her ideas have made "no change". However, she does have a new diagram. This diagram shows the sun, two trees and the observer. There are light rays from the sun to the farthest tree from the observer, which are reflecting to the far side of the nearest tree. There is also one ray from the sun to the nearest tree which is reflecting to the observer's eyes. Again, Cari is still working on resolving the shadow-reflection question to her own satisfaction.

Theories of Colour

After the researcher's introduction (see Appendix D), the class moves into small groups. Cari is working out how to experimentally investigate how we see colour.

Researcher: How do we prove that you're right?

Cari: With an experiment.

(And further on):

Researcher: What do think Cari?

Cari: I think it's the white one, the object one. It's just like the object and that's the (inaudible) colour. Then if you shone like that coloured light on it, then it doesn't appear, like the book doesn't appear blue but not like....

(And further on):

Cari: You just have to like shine the same colours on (inaudible).

Cari Cari and the others are working out how they might perform an experiment to test their ideas about how we see colours. Basically, Cari is suggesting that coloured lights should be shone on various coloured objects, and the results noted. Cari works out how one variable needs to be controlled.

Researcher: What I'm trying to get at is if we did it in this room (the classroom), what would be the problem?

Cari: There's other lights, there's other lights around

Researcher: Right. So where are we going to have do it, Cari?

Cari: In the storage room.

Cari is pointing out that to do the experiment properly, there must be only one source of light in the room, the coloured light, and that all other light sources must be as far as possible eliminated. What is needed is such a location. Cari suggests the storage room.

Later on, Cari joins with other members of her group in predicting results of some hypothetical experiments:

> Researcher: And if I shone a green light on a red object, what would you expect to see?
>
> Cari: It'd be like whatever....
>
> Another student: Orangey
>
> Cari: Yeah, orange or whatever those colours make.
>
> Researcher: You think they'd mix.
>
> Cari: Yeah, and then like you take the colours, you mix them, then it'll turn into a different colour which would be (inaudible) colour.

Cari is clearly speaking from the viewpoint that colours of light and colours of objects mix together and that what will be seen is a combination of the two.

Further on, Cari uses an analogy to develop an argument for her idea of a combination of light and colour:

> Cari: Say you take paint and then you don't have a certain colour, then you can mix colours to make it.
>
> And she repeats her idea.
>
> Cari: The colours, you mix them like. If you take certain colours and you mix them it would turn into a different colour.

Cari is using what she knows about mixing paints to support her argument about coloured light and coloured objects. Now she draws her conclusion.

> Cari: If you have a blue thing and then shine green light on it, it would come out, like, blue and yellow would make green. And if you had a blue book and a yellow light, then the book would look green.

She now makes the connection and applies her idea about paint to light and objects.

In her journal, Cari writes that her ideas about how we see objects have not changed. However, she does make a new entry about colour: "Lights mix colours so you see different colours." Although objects are not specifically mentioned, this is probably a statement of her idea that colours of light and colours of objects combine.

Evidence for Theories of Colour

After receiving instructions about aims and materials (see Appendix D), the students broke into their small groups. Cari's group begins by trying some combinations of coloured light and coloured squares of paper. There is some disagreements about the perceived results.

> Cari: What colour is that? Orange and yellow? No, no, orange. Yellow and red make orange. Ha, you weren't right.

Cari now is taking the opportunity to test her predictions about the mixing of colours of light and colours of objects.

Later, Cari tries to explain why the light appears coloured after it travels through a coloured filter.

> Researcher: First of all explain to me why these lights come through here coloured.
>
> Cari: Because that's coloured.
>
> Researcher: But how does that exactly work, Cari?
>
> Cari: The light picks up the colour from it.

This is the same view Cari expressed in her pre-evaluation and her pre-interview, that is, that white light is pure and colourless and the filters "add" colour to the white light.

More experiments with coloured light and coloured objects are performed and more disagreements arise about what are perceived as the results.

> Researcher: What colour is that Cari?
>
> Cari: Green, green colour.
>
> Another Student: No, it's dark dark yellow.
>
> Researcher: What colour is that?
>
> Another student: Black.
>
> Cari: Green, it's dark green.

These disagreements remain unresolved and continue.

Another experiment is performed to compare what is perceived when the filter is laid right on top of the object, rather than held in front of where the light emits from the light box.

> Cari: When you let the light in it's dark green.
>
> Researcher: Ah, okay. lay that on top there.
>
> Another student: That's black.
>
> Researcher: Why?
>
> Other students: Because it's darker with that right on it. There's no light coming through. Yeah.
>
> Researcher: Exactly.
>
> Cari: But when you let the light come through then it's green, dark green.

Cari does not dispute that the object appears black when the filter is laid right on top of it. But she still retains her view that when the filter is placed further away, the object appears dark green. She also reasons that this is because when the filter is further away, light other than that which travels through the filter hits the object, that is, "When you let the light through then it's green, dark green."

The dispute about what colours are perceived continues to the end of the small group session. At one point, it is suggested that someone in the group must be colourblind. When speculating on what might be some explanations for the different perceptions, at least three possibilities come to mind. One, human abilities to perceive colour differ. Two, the observers bring certain theoretical expectations to their perceptions, that is, they see what they want to see. Three, social factors cause the boys to band together on one viewpoint and the girls to band together on the other viewpoint.

Cari makes a contribution to the whole class discussion after the experiments are completed.

Researcher: What did you see, Cari?

Cari: When we had all the colours you shone a white light on it and it came out white.

Researcher: What's a possible explanation?

Cari: That white is all colours.

Cari's comment is in reference to a demonstration where the researcher placed three coloured filters one on top of the other and shone a beam of white light through the combined filters. Cari's explanation of why the light on the other side looked white is scientifically correct.

Cari's journal shows that her thinking is pretty much the same as before. Regarding how we see objects, she writes that her ideas show "no change". Her entry about why objects appear coloured when we look at them is that "light mixes with the colours." This seems to be just a clearer formulation of what she wrote after the previous lesson, and a further expression of the theory of colour and light which she continues to hold.

Reflection Theory of Colour

Cari does not participate in the discussion during the researcher's presentation of the reflection theory of colour (see Appendix D). In her journal she writes that her ideas show "no change".

DISCUSSION OF ALL RESPONSES

Students seemed to develop more scientific understanding of natural phenomena as the instructional intervention progressed. However, there was variety in "success" across the entire group of students. Some students started out with scientific conceptions and retained them throughout. They were able to assimilate the new information and experiences into their scientific conception, for example, Gary, Miles, and William began with scientific conceptions and held to them. They assimilated the new idea that white light is composed of all colours. Some students began with spontaneous conceptions and began to develop more scientific conception. For example, Barbara, Sam, Heidi, Laurie, and Hilary slowly changed their conceptions as the intervention progressed. Their journals provided a record of these changes and helped reveal what events were most significant in effecting these changes. Some students began with spontaneous conceptions and did not change them. They were unable to make sense of their new experiences. For example, Robert mentioned several times that the new ideas were confusing him. Zelda, while she did not state that she was confused, showed in her comments that she was unable to integrate new knowledge into a new conception. Some students were able to change their thinking on only one of seeing or colour, keeping the same spontaneous conception on the other. They were not able to see that seeing and colour are related and that conceptions of one hold implications for conceptions of the other. For example, Monty and Tricia seemed to adhere to a visual rays/illumination idea of seeing while at the same time came to accept a reflection conception of colour. Finally, at least one student started with a scientific conception and then seemed to move further away from it. Donald "knew" it was reflection at the start of the intervention but as the intervention progressed questioned his conception more and more. Perhaps this shows that his understanding of the scientific conception was not deep.

The journals provided valuable information about the individual students but did not prove as successful as had been hoped. The entries were often brief and, as noted, at least half the entries were of the "my ideas have not changed" type. The latter may have been an honest appraisal. It would have been more productive for research and instructional purposes if the students had been able to write something else. The instruction that they could simply write "my ideas have not changed" was probably poorly conceived. As pointed out, the use of science response journals is new. Conclusions based on them are quite speculative. It was pointed out to the researcher by another researcher who has done work on science journals (Kydd, 1988), that students need to develop skill using science journals over a period of time and that the students may have made better use of them had they had more experience in "journalling" (Kydd, personal communication, July 12, 1988). Better instructions might have been given to the students on how to use the journals. The instructions regarding the format were quite open-ended and still seem appropriate. However, limiting the student entries to the two questions, "How do we see objects?", and "Why do objects appear coloured when we look at them?", may have been too restrictive.

Perhaps students should have been instructed to describe their experiences and to draw conclusions from their experiences. Also, it might have been useful to ask the students to note some of their unanswered questions. Daily responses to the journal entries by the researcher might have been helpful. This would have provided instant feedback to individual students and allowed the researcher to interact daily, although briefly, with the conceptions of every student.

The main insight from the whole class discussions was that certain questions were raised repeatedly by the students and were discussed over an extended period of time. This suggests the importance of these particular issues. They may represent "critical barriers" to learning, that is, the clarification of them may be critical to students' understanding. The discussion of the "image" is instructive. The conclusion reached by some of the students, for example, Hilary and Allison, was that the idea of the image was absurd because it implied that objects did not exist. The students know objects exist. They have sense data to verify this knowledge. Thus, they are unable to accept the idea of the image since it goes directly against their experience. Of course, their conception of the image is not the one which the researcher was attempting to delineate, however, it is the conception on which they based any further understanding. The weakness of the researcher's explanation is that it is conceptual and not empirical. The researcher did not demonstrate in any empirical way the existence of the image. This points to the possibility of a better way of presenting the image so students could have direct experience of it. The image appears as a critical idea. At the same time, acceptance of the image does not guarantee a new conception. A number of students accepted the idea of the image but still talked about "seeing" the image, that is, there is an image but it still must be seen through some kind of separate, overt, external act. In other words, they were able to assimilate the idea of the image into their spontaneous conception.

The whole class discussions revealed that everyday use of language can influence students' understanding of natural phenomena. The discussion between the researcher and Allison is instructive on the issue of "visual rays". At first, it appeared that Allison did hold to a "visual rays" theory of seeing. However, as the conversation developed, it became clear that the thrust of her objections was that she felt that rejection of an act of seeing denied that the eye has any role in seeing. This was absurd to her because she knew that the eye does play a role in seeing and that we cannot see objects if we are not "looking at" them. Allison pointed this out to the researcher by giving the example that she could not see anything if her back was turned to what she was trying to see. Eventually, Allison seemed to accept the compromise that "looking at" objects could also mean that the eye is in a position to receive reflected light. Her opposition to the reflection theory of light, then, may have partly been because, in everyday language, we talk about "seeing" objects, rather than about objects "reflecting light to our eyes". Perhaps, then, the students did not so much hold to a visual rays type of understanding of seeing as to a "commonsense" understanding. More questioning should have been done to actually determine if the students conceived of something emitted from the eye when they spoke of "view" and "line of sight".

The class discussions also revealed some possible ways to evaluate ongoing understanding. Two of these ways were the nature of the discussion and the nature of the questions. The nature of the discussion showed what ideas some of the students held; how they perceived those ideas; what evidence supported their ideas; whether or not their ideas were changing; and what may have caused their ideas to change. Their ability to explain their own ideas to others gave some indication of the depth of their understanding, that is, how well they understood their conception. At the same time, it must be noted that participation in discussion was not correlated with improved understanding. Some students participated but did not change their understanding, while others did not participate or participated very little and did change their understanding. The questions raised in the discussion also gave some indication of how well students were understanding. At first, questions were raised by the researcher. The students began to provide answers to the researcher's questions. The "level" of researcher questions varied, that is, from fact recall to "why". The students also began to ask questions. Again, these questions varied as to their "level", for example, some were procedural and others were conceptual. Student questions were at first answered by the researcher. Later some were answered by the students themselves. Eventually, students began raising "high level" questions, such as, "If black absorbs all colours of light and we see by light reflecting to our eyes, how can we see black?", and then answering some of these questions themselves through outside research. This meant students were "empowered" to initiate their own learning outside the classroom, a giant step forward. It was, however, also noted that not all students were participating in the questioning and that some were participating to a greater extent than others, for example, Donald and Maurice.

The small group discussions brought to the fore at least four more important issues which were, at most, barely touched on by the journals and the whole class discussions. One of these was that students may hold the right answer for the wrong reason. This is important because it has direct implications for how we may evaluate student understanding. During the work on colour, Shawn, for example, declared that a red object under green light appeared black, while Cari disagreed and said it was not black but dark green. Assuming these two students were tested on this problem on a fact recall type of exam, possibly a multiple choice exam, Shawn would select "black" as his answer while Cari would pick "dark green". Shawn would, therefore, be "right" while Cari would be "wrong". However, further discussion with Shawn and Cari about their responses shows that both Shawn and Cari have the same level of understanding of the phenomenon, that is, both believe that the colour they perceive, whether black or dark green, is a result of the mixing of the green light and the red object. Both think of colour as an innate property of objects. Although Shawn's answer of "black" is theoretically correct, the scientific reason for the red object appearing black is rather that the red object absorbs all the green light. Shawn may be able to give the "right" answer on a recall-type test but he has no better understanding than Cari of the scientific conception of why the red object appears black. The nature of his understanding is not revealed by his selecting the correct answer but by further discussion and explanation of the basis for his ideas.

The same discussion about what colour the red object appears under green light also indirectly brought out several additional points about students' understanding of the nature of scientific knowledge. The students in the small group asserted that their particular perception of the colour was correct, gained allies for their view, appealed to authority, and suggested that those who disagreed with them must be colour-blind. This whole debate highlights the difficulty in teaching for understanding. As noted above, the disagreement about the colour of the red object turned out to be unimportant because both Shawn and Cari had the same underlying conception of why it appeared that colour, that is, each thought that the colour they saw was the result of the mixing of the green of the light with the red of the pot. However, the ongoing debate about the colour and how it developed brought out several very important points about scientific knowledge: the authority for knowledge claims; the difficulty that students have in "agreeing to disagree"; and the role of subjectivity. Without knowledge of the actual debate, these points would probably be missed because they would not be revealed by any "product" evaluation.

From their experiments on seeing and colour, the students in the small group, as well as the rest of students, drew various conclusions. In the small group, the researcher attempted to assist the students in conducting and understanding their experiments. Still, sometimes the students drew conclusions supporting their spontaneous conceptions, while at others they drew conclusions supporting more scientific conceptions. Even with teacher guidance, then, there is no "guarantee" that certain experiments will lead students to certain conclusions. Testing a theory by experiment is a complex process. Usually an overall theory cannot be directly tested because it involves transobservational concepts not linked to any empirical concepts. Testing a theory experimentally requires adding subsidiary assumptions, which the theory does not contain because it is general by nature, in order to construct a theoretical model (Bunge, 1973). This was done by the researcher when he added the subsidiary assumptions about the nature of white light to the general theory of colour by reflection. After the model is tested, the data must be used to draw some plausible conclusions about the worth of the theory. Data may be distorted by poor experimental design. For example, the coloured filters in the colour experiments may not have completely eliminated the other colours in white light. Observations may be influenced by preconceptions. For example, Cari may have "expected" to see dark-green" in the green light-red object experiment. Conclusions drawn from data may also be influenced by spontaneous conceptions. Both Cari and Shawn may have gone into their experiment "expecting" to prove that the colour they perceived was mixture of red and green. If experiments are to be considered an important aspect of science, then, both teacher and students must continually work to improve their ability to conduct them.

THE HISTORY OF SCIENCE

During the early historical development of scientific ideas regarding seeing and colour, contradictory theories tended to coexist. Theories were put forward, developed, altered, challenged, opposed, discarded. Both logical and experimental evidence were used in these endeavors. In the historical development of the scientific theory of seeing, the work of Al-Hazen (10th century) is considered a turning point, while in the development of the scientific theory of colour this honor is usually given to Newton (1704). After their advent, the basic foundations of each theory were laid and subsequent developments tended to clarify rather than to oppose these basic foundations. There are, again, some parallels between the above history and the process of enquiry which the students in the study went through during the instructional intervention. They articulated their own ideas, they considered other possible explanations, they discussed and debated, they performed experiments, and they tried to draw conclusions from them. In some cases their ideas changed, in others they did not. During this process of inquiry, they at times took up arguments about seeing and colour which were similar to some of those found in the history of science. They also at times devised experiments involving seeing and colour which were similar to some of those found in the history of science.

One example of an argument taken up by the students which has parallels in the history of science concerns the discussion of the eye and reflected light. It was suggested by some of the students in the study that the fact that the eye is hurt by sunlight reflected off an extremely bright white surface is evidence against the reflection theory of seeing. The students concluded that the constant reflection of light into the eye would result in permanent eye damage and the inability eventually to see anything. In the 10th century, Al-Hazen noted the same effect of light on the eye: "We find that when the eye looks into exceedingly bright lights, it suffers greatly because of them and is injured; for when an observer looks at the body of the sun, he cannot behold it well, since his eye experiences pain because of the light. Similarly, when he looks into a polished mirror, above which rises the light of the sun, and his eye is in the place to which the light is reflected by the mirror, he will again experience pain because of the reflected light reaching his eye from the mirror, and he will not be able to open his eyes to observe the light" (Lindberg, 1976, p. 61-62). Al-Hazen, however, rather than using the above observation as a refutation of intromission, used it as a refutation of the extramission theory of vision. Al-Hazen concluded that since the injury is inflicted by an external agent, this showed that in the visual process the eye must receive some external action rather than transmit something.

An example of an experiment which the students devised during the study which has parallels in the history of science was their use of prisms to break up white light into its colours. Newton used the same procedure and concluded from the results that white light was not pure and colourless but was made up of all colours. This discovery was critical to the new conception of colour. It led Newton to suggest that colour was the result of an interaction between light and the object, rather than an innate property of objects. The example of Al-Hazen's argument and of Newton's experiment, then, point the way to an important use of the history of science in teaching science. The history of science can provide both arguments and experiments which may prove useful both to students and teachers in their investigations of natural phenomena. A knowledge of the history of science can help the teacher develop instructional approaches and also provide her with examples and arguments through which she can help students clarify their understanding. Finally, a knowledge of the history of science may even help the teacher anticipate student questions. During the study, one student, Sam, suggested that since people who are colourblind see colours differently than "normal" people, how do we know that red, for example, is really red?. The cousin of physicist Max Born asked Born the same question in his school years, and Born returned to it again and again throughout his life. Kant, Bertrand Russell, Ernst Mach, and Derek Hume were other philosophers and scientists who also tried at some time in their lives to provide satisfactory answers to this question (Naletov, 1984).

Part Three: Students' Conceptions After Intervention

DATA SOURCES

The purpose of the post-evaluations, the post-interviews, and the final journal entries was to discover what conceptions of seeing and colour which students held at the end of the study. The post-evaluations consisted of the same ten questions as the pre-evaluations. The post-interviews, also consisted of the same ten questions, accompanied by mini-demonstrations, and were administered to the same five students who were pre-interviewed. The journal entries were to focus on the two general questions: "How do people see objects?" and, "Why do objects appear coloured when we look at them?" The journal entries did not provide much information beyond the post-evaluations because entries were brief and almost always duplicated the post-evaluations. Therefore, the post-evaluations and the post-interviews are used as the main data source for the students' "final" conceptions. Twenty-nine post-evaluations were collected and analyzed.

IDEAS OF THE WHOLE CLASS

How Does Light Help Us to See Objects?

The responses to this question were categorized into four groups: illumination, reflection, reflection to the eye, and reflection with image. One student left this question blank. Five students gave an illumination response, that is, they made no mention of reflection. Their answers were expressed in terms such as "If there was no light there would be no colours", "(Light) brightens them up", and "Light shines on everything". Eight students gave a reflection response. They mentioned light as reflecting off the object but did not mention the eye or the image. Nine students stated that light reflected off the object to the eye, but made no mention of an image. Finally, the remaining six students mentioned reflection and the image. Their answers were in terms such as "It helps us to see objects because light comes down and reflects off the object to your eye and that makes an image in your eye of the object and that's how you can see", "It reflects off the object into our eye and we see an image", "It bounces off the object we are looking at then the light bounces off the back of our eyes and we see the object", and, "It goes onto an object and sends an image of the real object to our eyes, then the image goes into the back of our eyes." Over-all, then, twenty-two students made some mention of reflection in their answers.

Draw Arrows to Show How Light From the Sun Helps the Girl See the Tree.

The diagrams depicted three conceptions of seeing, illumination, visual rays, and reflection. One student drew arrows from the sun to everywhere in the diagram, and wrote "brightens up" and "bright" on the tree. Eight students drew some kind of visual ray from the girl to the tree. In two of these diagrams, rays were also shown reflecting from the tree to the girl. The remaining twenty students drew an arrow or arrows from the sun to the tree reflecting to the eye of the girl.

Why Can't John See the Penny in the Bucket?

The students gave three types of answer to this question, except for one who gave no answer. The three types of answers were "could but can"t", "blocked line of sight", and "blocked reflected light". Eleven students suggested that the edge of the bucket was not between John and the penny but that there was some other factor preventing him from seeing the penny. These factors were variously given as same colour as the bucket, glare, shade, darkness, and inattention. Fourteen students responded that the side of the bucket was blocking John's "line of sight", either in words or by drawing a line from John's eyes which did not strike the penny. This was expressed in terms such as, "The container is too big and cuts off his vision", "The bucket blocks his point of view", "John can not see far enough down in the bucket", and "The side of the bucket is hiding the penny". The remaining three students responded that John could not see the penny because the reflected light could not get to his eyes. Their answers were, "John can't see the penny because the light reflected off the penny can't get to his eyes", "The light shines on the penny and then the light can't get to your eyes", and, "John cannot see the penny because no reflection will hit John's eyes." These last three students, then, were able to apply the scientific theory of how we see to the problem.

Why Can John See the Penny After the Bucket is Filled With Water?

The responses to this question fitted into five categories, called, respectively, "relocation by reflection", "elimination", "magnification", "redirection", and "seeing by reflection". Two students responded, "I don't know". In relocation by reflection, the basic premise was that the water had "reflected" the penny to a new location where John can see it. The side or edge of the bucket was still between the penny and John but was not between the "reflection" of the penny and John. This relocation was expressed in terms such as, "The light shining on the penny makes a reflection", and "The image of the penny is reflected in the water". Some students actually drew the "reflection" in a new location. In this explanation, instead of seeing the actual penny, then, John sees its reflection at a new location. This seeing, however, is not connected to reflected light. Nine students gave this type of explanation.

The elimination idea was presented by those students who had previously suggested that John actually "could" see the penny but there was some other factor such as glare, shadow, or lack of contrast. Following from their initial premise, these students stated that the water had eliminated what they saw as the source of the problem. Ten students gave this type of response.

The basis of the magnification idea was that John could see the penny because somehow the water made the penny look larger or closer. In other words, the water acted like a lens. Two students gave this answer.

Three students showed a "line of sight" coming from John's eyes which was redirected toward the penny by being bent downward as it entered the water.

The last three students expressed the idea that the light reflected off the penny was deflected by the water so it could reach John's eyes. The three answers were, "He can see it now because the water scatters the light reflects off the object then goes to his eyes", "The light reflects off and into his eyes", and "He can see the penny because the light is reflecting off the water". These last three students, then, seemed to have a scientific explanation for why John could see the penny.

What Happens to the Light From the Flashlight After It Hits the Objects?

The four objects were a mirror, a piece of translucent glass, a piece of clear glass, and a piece of white wood. For the mirror, all twenty-nine students drew arrows or wrote answers which showed that the light reflected back off the mirror. Of these, about twenty drew their arrows in a manner which appeared to represent an attempt to show the reflected rays rebounding at the same angle as the incident rays.

For the translucent glass, ten students thought that the light would stay on or stay in or stop on or be absorbed by the object. In other words, the journey of the light would somehow end at the translucent glass. These students made no mention of reflection at all. Six students thought that the light would go straight through the frosted glass. In other words, they gave the same answer for the frosted glass as they did for the clear glass. None of these students made any mention of reflection. Three students thought the light would just reflect off, that is, the translucent glass would act like a mirror. Nine students thought that some of the light would go straight through the translucent glass and that some would be reflected off. However, only three of these nine students drew a diagram which seemed to show the light scattering rather than reflecting off coherently. The latter represents the scientific explanation of what would happen to the light, that is, the light would both reflect and scatter, and go through and scatter. Only three of the students, then, seemed to understand the scientific conception of scattering.

Twenty-five of the twenty-nine students used arrows to show the light travelling straight through the clear glass and beyond it. This is a scientific understanding of this phenomenon. The other four students used arrows to show the light travelling through the clear glass, but also drew arrows to show that some light reflected off the glass. These latter four students may have a deeper understanding than those who only drew the light going right through, since they may be illustrating the idea that, although the majority of light travels coherently through clear glass, the glass would be visible only if at least some light was reflected off it. As a whole, then, the class understood that light passes coherently through clear glass.

For the white wood, ten of the students depicted the light as stopping at the wood. This was described in various terms, one of which was that the wood "absorbs" the light. These students, then, believed that the light would not reflect off the wood. Two students thought that the light would go through the wood. The other seventeen students depicted the light reflecting off the wood. Seven of these seventeen drew diagrams which, when compared with their mirror diagrams, seemed to show the light scattering rather than being reflected coherently, and one of them actually stated that the light would "scatter. Seventeen of the students, then, presented the basic scientific conception that light would reflect off the white wood. Of these seventeen, seven seemed to be demonstrating a deeper understanding by trying to show that the light reflected from the white wood in a different manner than from the mirror, that is, that light scattered from the white wood.

Why Does a Black Object Look Darker Than a Grey Object?

Five students left this question blank. One student said that black is all colours while another said that black has fewer colours. One student gave an answer to this question which simply restated the question. That is, she stated that black looks darker than grey because black is darker than grey. These students, then, see no connection between light and colour.

Twenty-one students stated their answers in terms of one or both of absorption and reflection. They stated that black absorbs more light than grey and/or that grey reflects more light than black. Two of these students used the word "reflects" where scientifically they should have used "absorbs". These students understand that colour involves an interaction between the object and light, whereby light is absorbed and/or reflected by the object to varying degrees. This is the scientific explanation of why black looks darker than gray. Just over two-thirds of the students, then, held a scientific conception of this phenomenon.

What Does the Coloured Glass Do to the White Light Shone Through It?

As this question was a multiple choice question, the answers can be simply categorized by which of the four choices was selected. Three of the students did not answer. Two of the students selected (a) The glass adds red colour to the light. These students, then, assumed that white light is pure and colourless and that colour is something which the red glass added to the white light. Two of the students selected (d) The glass turns the white light into red light. Again, these students assumed that white light is pure and colourless and that colour is something which the red glass added to the white light. Six of the students selected (b) The glass lets all the light through but stops all the colours except red. This answer also assumes that light and colour are separate phenomena. Sixteen of the students selected (c) The glass lets red light through but stops all the other kinds of light. This answer assumes that white light is made up of all colours, and that the red glass stops all the colours other than red. That is, the filter performs a "subtractive" rather than an "additive" function. (C), then, is the scientific conception of what happens to the white light at the red filter. Just over half the students chose this conception as the best explanation.

What Colour Will the Green Plant Appear in Green Light? Why?

One student did not answer. Two students suggested the plant would appear a colour other than green. They thought that this new colour would be a result of the green of the light and/or the plant mixing with the red of the pot. The result of this combination was stated as red-green and black, respectively. These two students are assuming that colour is an innate property of objects, and that light is an external factor which "adds in".

Twenty-six of the students stated that the plant would appear green or some shade of green. Of these twenty-six, eighteen did not explain their reasoning in terms of reflection and/or absorption. Instead they made statements such as "There is only green light", "The green light won't affect the plant", and "The light is green and the plant is green". These students, then, also see light and colour as separate, that is, colour is an innate property of objects and light is an external factor which illuminates the coloured object. The other eight of these twenty-six made some reference to reflection. This was in terms such as, "Green because it is only reflecting green light", and "There is only green light to reflect and no light to absorb". These eight students are applying the concept of reflection to colour and seem to have a scientific understanding of why the plant appears green in green light.

What Colour Will the Red Pot Appear in Green Light? Why?

Two students did not answer the question. Seven students thought the pot would appear green and one thought it would appear red. The colour was described as being due to the predomination of either the green light, the green plant, the green light and the green plant, or the red pot. All these students see colour as innate in objects. To them, light and colour do not interact at all but are separate phenomena.

Fourteen students thought that the green of the light and the red of the pot would combine to make a new colour. The majority of these students predicted that this new colour would be either black (11) but brown (2) and "whatever green and red make" were also mentioned These students conceive of light and colour as interacting, but see this as a process of mixing rather than reflection and absorption.

The remaining seven students stated that the pot would appear black and attributed this to the fact that the red pot would absorb the green light, leaving no light to be reflected, and so would appear black. These seven students, then, correctly applied the scientific principles of absorption and reflection to this problem.

Why Does a Blue Book Appear Blue?

As this question was a multiple choice question, the answers can be simply categorized by which of the four choices was selected. Two students did not answer the question. One students selected (a) The light helps our eyes to see the blue colour of the book. This student conceives of colour as an innate property of objects. The colour is "there" and we "see it" when it is illuminated by light. Seven students selected (b) The book absorbs blue light and reflects other colours. These student are applying the principles of absorption and reflection to colour but are confused as to the scientific meaning of each principle. The remaining nineteen students selected (c) The book reflects blue light and absorbs other colours. These students are applying the principles of absorption and reflection to colour. The answer they have selected is the scientific conception of this phenomenon.

Why Are There Only Three Primary Colours of Light And Not Some Other Number?

Nine students did not answer this question. One student suggested that, "These colours make white". Sixteen students answered that there are only three primary colours because all the other colours can be made from these three primary colours. This answer is a definition of primary colours but is not an explanation, that is, it does not tell why there are only three primary colours and not some other number. The remaining three students connected the number of primary colours with the three types of colour-sensitive cones in the eyes. Three of the students, then, gave a scientific explanation.

What Are the Three Primary Colours of Light?

Two students did not answer the question. One student suggested "Blue, black, white", and another suggested, "Red, orange, yellow". Eight students wrote down red, yellow, and blue, the primary colours of pigments. One student wrote "Red, yellow, and blue or Blue, green, and red". The other sixteen students wrote "Blue, green, and red", which are the primary colours of light. These sixteen students, then, gave the scientific answer.

TABLE OF RESULTS
Students' Conceptions Before and After Intervention

How Does Light Help Us To See Objects?

	Before	After
Illumination	17(65%)	5(17%)
Reflection	9(34%)	24(83%)

Draw Arrows to Show How Light from the Sun Helps the Girl to See the Tree.

	Before	After
Illumination	7 (27%)	1 (3%)
Visual Rays	10 (38%)	6 (21%)
Two-Way	4 (15%)	2 (6%)
Reflection	5 (19%)	20 (69%)

Why Can't John See the Penny in the Bucket?

	Before	After
Line of Sight	11 (42%)	14 (48%)
Could But Can't	10 (38%)	11 (38%)
Reflection	2 (8%)	3 (10%)
Other	3 (12%)	1 (3%)

Why Can John See the Penny After the Bucket is Filled With Water?

	Before	After
Relocation of penny by reflection	10 (38%)	9 (31%)
Elimination	9 (35%)	10 (34%)
Magnification of penny	3 (12%)	2 (7%)
Redirection of sight	1 (4%)	3(10%)
See by reflection	2 (8%)	3(10%)
Other	1 (4%)	2 (7%)

What Happens to the Light From the Flashlight After it Hits the Objects?

	Mirror	
	Before	After
Reflect	25 (96%)	29 (100%)
of which		
Incident=Reflection	15 (60%)	20 (69%)
Other	10 (40%)	9 (31%)
Other	1 (4%)	

Table of Results (continued)

Translucent Glass

	Before	After
Stay On	11.5 (44%)	10 (34%)
Go Through	7 (27%)	6 (21%)
Reflect	0 (0%)	3 (10%)
Go Through and Reflect	7 (27%)	9 (31%)
of which		
Coherently	6 (86%)	6 (67%)
Scatter	1 (14%)	3 (33%)

Clear Glass

	Before	After
Through	22(85%)	25(86%)
Stop	2 (8%)	0 (0%)
Through and Reflect	2 (8%)	4(14%)

White Wood

	Before	After
Stop	13(50%)	10(34%)
Through	0 (0%)	2 (7%)
Absorb and Reflect	5(19%)	0 (0%)
Reflect	8(31%)	17(59%)
of which		
Coherently	4(50%)	10(59%)
Scatter	4(50%)	7(41%)

Why Does a Black Object Look Darker Than a Grey Object?

	Before	After
Restate question	11(42%)	1 (3%)
Absorption and Reflection	15(58%)	21(72%)
Other	0 (0%)	7(24%)

What Does the Coloured Glass Do to the Light Shone Through it?

	Before	After
Glass adds red colour to the light	10(38%)	2 (7%)
Glass lets all light through but stops all colours except red	4(15%)	6(21%)
Glass lets red light through but stops all other colours	4(15%)	16(55%)
Glass turns white light into red light	5(19%)	2 (7%)
No answer	3(12%)	3(10%)

Table of Results (continued)

What Colour Will the Green Plant Appear in Green Light?

	Before	**After**
Not green	10(38%)	2 (7%)
of which		
Mixture	8(80%)	2(100%)
Other	2(20%)	
Green	16(62%)	26(90%)
of which		
No reflection	13(81%)	18(69%)
Reflection	3(19%)	8(31%)
No answer		1

What Colour Will the Red Pot Appear in Green Light?

	Before	**After**
Green or red	7(27%)	8(28%)
of which		
Green	2.5(36%)	7(88%)
Red	4.5(64%)	1(13%)
Green plus red	19(73%)	14(54%)
Black by reflection/absorption	0 (0%)	7(24%)
Other	4(15%)	0 (0%)

Why Does a Blue Book Appear Blue?

	Before	**After**
Light helps our eyes see the blue colour	15(58%)	1 (3%)
Book absorbs blue light and reflects other colours	1 (4%)	7(24%)
Book reflects blue light and absorbs other colours	10(38%)	19(66%)
No answer		2

Why Are There Only Three Primary Colours of Light?

	Before	**After**
Make all other colours	14(54%)	16(55%)
No answer	8(31%)	9(31%)
Miscellaneous	4(15%)	1 (3%)
Match cones in our eyes	0 (0%)	3(10%)

What Are the Three Primary Colours of light?

	Before	**After**
Red, yellow, blue	18(69%)	8(28%)
Other	8(31%)	5(17%)
Blue, green, red	0 (0%)	16(55%)

INDIVIDUAL CASE STUDIES

Shawn

How Does Light Help Us to See Objects?

Shawn's post-evaluation gives a different answer than his pre-evaluation to this question. He writes: "Light helps us see objects because it makes up the object and reflects off and all sorts of things." Shawn reveals his thinking has taken an important step forward here. His reference to, "Light...makes up the object", shows he has at least partially grasped the notion of a light image. He also has retained his idea of reflection as integral to seeing. At the same time, his concluding phrase, "And all sorts of things", shows he is still not clear in his thinking. He made no mention of the role of the eye, even though he dwelt for some time on the "screen" and the "special cells" during the interventions. The rays Shawn draws on the diagram of the observer and the tree show light travelling from the sun to the tree and then to the eye of the observer (Diagram 9). There are no visual rays travelling back to the object at all showing he has now discarded this idea.

In his post-interview question about how we see Shawn does refer to the "little screen". He explains how the light helps him to see a chair in the room.

> Shawn: Well, the light shines down in my eye. No, the light shines down on the object and the object would be Matt's chair. And then in my eye and on that little screen. And then the screen makes out what it is, and then that's how we see it.
>
> Researcher: How does the screen make out what it is? What happens between the eye, your eye and the object, or the object and your eye?
>
> Shawn: Well, what was that again?

> Researcher: Well, you said the light shone down on the desk. And then you said, so I was just asking what happens between your eye and the object?
>
> Shawn: It shows what should, what should make up the object and then special little cells and stuff. Well, when there's no light on the screen, then we can't see anything. And then when there's light and I look at that, then the light makes, then there's light in the screen. And then the little screen makes up what should be out there.

Again, it appears that Shawn has put together reflection with the functioning of the eye. However, he has made no direct mention at all in his description of the reflected image. Perhaps, though, his comments about the little screen could be an indirect way of talking about the image, that is, the screen is where the image falls.

Why Can't John See the Penny in the Bucket?

In the post-evaluation, Shawn's thinking on the penny problem is also somewhat different from his thinking on the same problem on the pre-evaluation. On his post-evaluation, on the first diagram where there is only air in the container, he writes: "The light shines on the object and then the light can't get to your eyes." Shawn's added rays in this diagram are similar to those added in his pre-evaluation except that now the rays from the light bulb have directional arrows into the container (Diagram 10). Also, he has omitted the notion that "light moves around inside the container". Further, he has written the comment, "Can't go to his eyes", beneath the observer in the diagram. Although all this is not a clear presentation of the reflection theory, Shawn seems to be more on this track than in his pre-evaluation because he has specifically noted that the reflected light cannot get to the eyes of the observer. Again, however, he may have in mind only illuminating light rather than a reflected image.

In the interview, Shawn states why John cannot see the penny.

> Shawn: There's no light reflecting off it. No, well the light, when there's like nothing in there, or something, probably the light shines down and then the light stays there because it can't reach my eye.

Shawn is quite firmly fixed on the need for reflected light but he still makes no mention of an image.

Why Can John See the Penny After the Bucket is Filled With Water?

Shawn's thinking about the second diagram involving the penny, when the water is in the container, is quite different from his thinking about the same diagram on the pre-evaluation (Diagram 11). He writes: "The light reflects off and into his eyes." This is a straightforward presentation of the reflection theory, although there is no mention of an image. Also, now Shawn has drawn rays of light right down to the penny beneath the water, whereas before his rays stopped at the surface and did not even reach the object. Further, he now shows a ray reflecting from the surface of the water to the observer's eyes, and writes, "goes to his eyes", beneath the observer. Again, although he does not mention an image, he is clearly showing seeing by reflection.

Shawn's explanation in the interview for why he now sees the penny is essentially the same as his view in the post-evaluation, although more succinct.

> Shawn: When there's water the light reflects off, the light reflects on the object and then reflects on the water and my eye.

Shawn's Ideas After Instructional Intervention

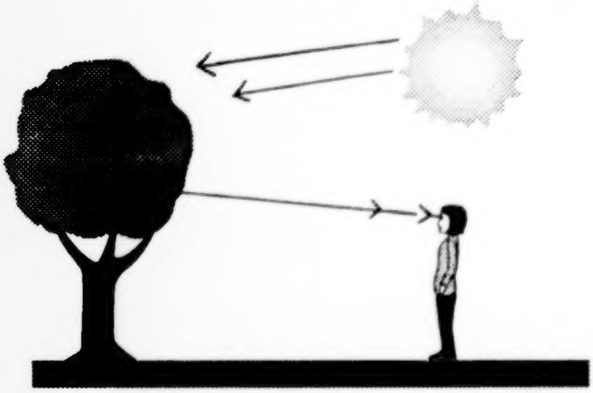

Diagram 9: *Draw arrows to show how light from the sun helps the girl to see objects.*

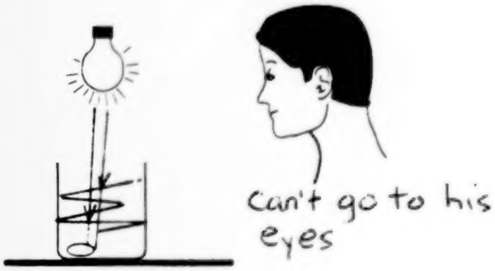
can't go to his
eyes

Diagram 10: *Why can't John see the penny in the bucket?*

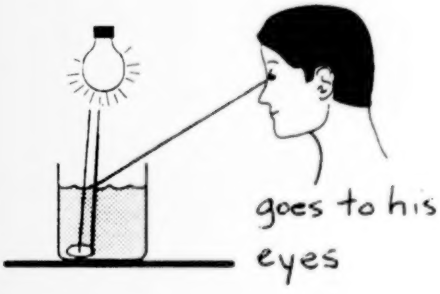
goes to his
eyes

Diagram 11: *Why can John see the penny after the bucket is filled with water?*

What Happens to Light From the Flashlight After it Hits the Objects?

Shawn's diagrams of what happens to the light from the flashlight after it hits each of the objects are unchanged in three cases: the mirror, the glass, and the white surface. This time Shawn has completely omitted any written commentary in all four cases. Perhaps he thinks it is unnecessary or perhaps he just does not want to do any writing. In the case of the frosted (translucent) glass, Shawn now shows the rays bouncing off the glass instead of spreading along it.

Shawn's post-interview views on what happens to the light when it hits the given objects are the same as on his post-evaluation, with one exception. After observing the light and the translucent plastic, he says: "It goes through sort of." He adds: "It goes through, it all goes through." This is directly opposite to his conclusion on the post-evaluation, where he said the light would bounce off the translucent material. The difference in his views may stem from the difference between actually observing a demonstration of how the light behaves with the translucent plastic as opposed to merely reading a problem and looking at a diagram.

After Shawn's answer about how the light would behave with the white wood, that is, would bounce off, the researcher used this answer to probe more deeply into Shawn's conception of reflection and seeing.

Researcher: Does any light off this bounce to your eye? Say, not necessarily from the flashlight but from the room light?

Shawn: No, probably not, maybe.

Researcher: How could you tell if light was bouncing off this to your eye?

Shawn: How would I know if what?

> Researcher: How would you know if light was reflecting off this white wood to your eye?
>
> Shawn: You would have to see the light, then. Cause then if the light from the room were bouncing off that, then the light would have to look like a flashlight probably. Because that's the only way you could see it. Well now, that's the only way you can know if it was.

Shawn's comments here suggest that he does not at all conceive of an image of the object reflected to the eye. His reasoning is that if any light was being reflected to his eye he would "have to see the light". In other words, direct perception is the proof for the existence of light reflected from the object. From his response to this question, he still thinks of the light reflected from the object as illumination rather than as an image.

Why Does a Black Object Look Darker to Us Than a Gray Object?

Shawn leaves this post-evaluation question blank. During the interview he gives quite a clear and lengthy commentary on the same question. His reasoning for the difference in darkness is:

> Shawn: Because the light absorbs the black more than the grey. Because it's darker and the black light brings in more of the light and so the light right there (on the black surface) sort of attracts more light. And so it absorbs it in. And the grey absorbs some but not all of the light like the black does.

Except for his reversal of causality in the first part of his description, Shawn here gives a correct scientific description of why the black surface looks darker, precisely describing the nature of absorption. The clarity of this verbal description makes his written omission on the post-evaluation all the more puzzling.

What Does the Coloured Glass Do to the White Light Shone Through It?

Shawn also does not answer this next question on the post-evaluation. His omission is puzzling since all he had to do was to underline one of several given alternatives. In the interview Shawn does give a description of what happens to the white light to make it look red: "Well, the white light goes in there and then it reflects all shades except for red and the red goes through." Again, except for his use of the word "reflection" where he should have used "absorption", Shawn is giving a scientific description of this phenomenon. He is also giving a different answer from his pre-evaluation and pre-interview, where he described the coloured filter as "adding" colour to the white light. He now seems to understand the nature of white light, that is, it is not pure and colourless but is made up of all colours.

What Colour Will the Green Plant Appear in Green Light?

Shawn gives basically the same answer as on his pre-evaluation to this question. On the post-evaluation he answers: "Green because there is only green light." However, he also adds a comment about how the plant would look in white light, showing he now understands that changes in appearance manifest themselves according to the colour of the light: "If there was normal light then everything would look normal and not change." This indicates he is moving away from the theory that colour is an innate property of objects and is beginning to think about the role of light in this regard.

In the post-interview Shawn also states that the plant will appear green. He then gives an explanation not directly related to the question.

> Shawn: If you had normal light, like right there, normal light shining down on, say, that orange one right there, then the orange object looks normal, right? And then if you had a green, if you had an orange light shining down on the whole room here, then that orange object, that

> green object right here would...all the shades would not look as clear as they might, like, in real life. And then so some of them might mix and change.

What Shawn is saying, it seems, is that although the object would look its usual colour in its "own" colour of light, that "usual" colour still might not appear quite "normal". Perhaps here Shawn is remembering some of the "weird" colours evoked by the coloured lights during the colour experiments. Certainly he is differentiating between objects seen in white light and objects seen in coloured light even when the coloured light matches the colour of the object in white light.

What Colour Will the Red Pot Appear in Green Light?

For the second part of the question, Shawn's answer on his post-evaluation is different from on his pre-evaluation. The red pot, seen in green light, will appear, "black because it absorbs the green light and then mix and darken." This answer shows Shawn is beginning to grasp the reflection theory of colour. The first part of his answer, "black because it absorbs green light", is scientifically correct. He has now added the conception of absorption of light to his understanding of how objects appear coloured. However, in the second part of his answer, Shawn wavers and falls back on the "mix" theory of colour: "and then mix and darken". In other words, Shawn still holds some allegiance to the idea that pigments and colours of light mix to create what the eye perceives. His thinking here is inconsistent because if green light is absorbed, then what is left to "mix and darken"? But at this time he seems to think of "absorption" as equivalent to or explained by some form of "mixing" of colour and light.

In the post-interview, Shawn's reply and explanation concerning the red pot in the green light is consistent with his remarks on the post-evaluation.

> Shawn: Well, probably the green light would absorb, would maybe absorb in the pot, sort of, and then it might look very dark, very dark. Not quite like black, but like very dark, dark, very dark green.
>
> Researcher: Why would it not look quite black? Why did you say that?
>
> Shawn: Well because the green light might, would, is not probably strong enough, so it probably wouldn't absorb that much. Like when I look at that, the black on that (he is referring to the black on the flashlight casing), the light really absorbs it. So if that was green light shining on that, that would really, really absorb it, and then the red, I mean the green light, wouldn't absorb in the red pot as much as it would in the black flashlight.

Again, Shawn is giving a very scientific description of absorption, even though he mixes up which agent is doing the absorbing, that is, he says that it is the light which is absorbing the colour of the pot, rather than vice versa. He still, however, refuses to grant that the red pot will actually appear black in green light. This hesitancy may be the result of his theoretical expectations, that is, that a "mixing" must take place. Or it may be due to his observations during the experiments, even though at that time he insisted that the paper perceived by others as dark, dark green was certainly black.

Why Does a Blue Book Appear Blue?

As he did on the pre-evaluation, Shawn chooses the correct scientific answer for the question about how we see the blue book, that is, "because the book reflects blue light and absorbs other colours". Shawn's explanation in the interview for why the book looks blue, however, is somewhat different.

> Shawn: Well, the light shines down on the object and then in my eye special cells, maybe there's special cells that like red, green, blue, and all that. And then they make up what it looks like and then you see it. And that's like with grass, right? When I look at grass and the light reflects in my eyes, maybe the cells, there's a green cell and the green cell makes it look like it should.

Here Shawn has gone back to his ideas about the light shining on the object and the special cells in the eyes. Colour seems once again to be separate from light, a property of the object. There is no mention of colour in terms of reflection and absorption of light.

Why Are There Only Three Primary Colours of Light? What Are They?

For this question, Shawn, who responded "I don't know" on the pre-evaluation, now answers that, "other colours can't mix". In other words he is now equating colours of light with colours of pigments. In the interview Shawn also suggests that the primary colours of light are the ones which can mix and make other colours, however, he also adds a comment about reflection and absorption, but trails off: "Well, maybe the three primaries, the ones that aren't primaries, can't mix, or they can't absorb or reflect or...." Now the idea of reflection and absorption in relation to seeing colour has come back to him. He does not develop it and simply leaves it.

Finally, Shawn now feels that the three primary colours of light are "red, blue, and green", instead of, as he wrote previously, "yellow, blue, red." Now he forgoes the analogy between light and pigments and gives the correct scientific answer regarding primary colours of light. He confirms this knowledge in the interview where he also names blue, red, and green as the three primary colours of light.

Paul's Ideas After Intervention

Paul's ideas after intervention are taken from his post-evaluation and his post-interview.

How Does Light Help Us to See Objects?

Paul states that light helps us see objects because "It reflects off the object and then we see it as an illusion". In his diagram, he only draws arrows travelling from the sun to the tree and the observer (Diagram 12). Above the tree he writes, "brightens up", and also writes "bright" right on the tree. Beside the observer he writes, "You see an illusion." He even draws a cartoon-like bubble above the observer's head, containing a small picture of the tree. Paul's understanding has moved well ahead from his pre-evaluation when he wrote merely that "you can't see anything without light". Now he is beginning to try to explain the actual mechanism by which light helps us see objects. He refers now both to reflection and to an image, although he calls the latter an "illusion". Paul's ideas about how light helps us see objects are coming quite close to the scientific explanation.

In his post-interview, Paul explains that light in the classroom comes from the lights, the sun, and the windows. He also again mentions "energy". The conversation then proceeds to how light helps us see.

Researcher: How does the light in this room help us to see Mark's desk over there. Can you explain that?

Paul: The light comes down on the desk and him. So it brightens it up so we can see it.

Researcher: What happens between his desk and your eye?

Paul: Reflection. It reflects off the desk at, kind of....

Researcher: What reflects off the desk?

Paul: The light reflects off the desk and brightens the desk up and the reflection brings an illusion to your eyes and then you can see.

Paul's explanation here is almost identical to the one on his pre-evaluation, particularly where he mentions reflection and the image (illusion). Again, his understanding of how light helps us see objects is very close to the scientific explanation.

Why Can't John See the Penny in the Bucket?

When asked on the post-evaluation about the penny in the bucket, Paul still seems confused about what the question is asking. He now writes that when the container is empty of water, "You can't see through the glass without water." He draws lines from the lightbulb to the far side of the container, from the observer's eyes to the container, and from the observer's eyes to the near side of the container (Diagram 13). His answer seems to have no connection with his previous explanation of how light helps us see objects.

Paul's comments during the post-interview about why he can't see the penny are quite different than on his post-evaluation, perhaps because for the former he is actually having to look for the penny. He now says that he can't see the penny "because there's nothing to, well the side of the cup is kind of in the way." When asked what the side is in the way of, Paul answers, "The penny. And in the way of my eyesight from seeing the penny." He also notes that the side is in the way "of the light", "the light that's coming from this side." He adds that, "The light hits from this side in." Paul is giving a common-sense answer here, that the side of the cup is in the way of his "eyesight". But he is also saying that the side of the container is blocking the light, perhaps meaning that if the penny is out of sight it must be in the "dark".

Why Can John See the Penny After the Bucket is Filled With Water?

On the post-evaluation, when the water is added to the container Paul says that he can see the penny because, "your eye sight is absorbed into the water, then reflected onto the object." He draws a line from the observer's eye to the far side of the cup at the water-line, then shows this line reflecting down onto the penny. He also again draws a line from the observer's eye to the near side of the container (Diagram 14). Paul is giving a straightforward "visual rays" answer to this question when he speaks of eyesight being "absorbed, then reflected." Although he has previously talked of reflection and images coming to the eye, he is unable to apply this conception to the new situation and instead falls back on the idea of visual rays from the eye to the object.

In his post-interview, Paul's answer is a little different.

> Paul: I think, well, the water kind of makes it like it was (inaudible) but then stay in the same spot. And you can kind of see it because I guess the water absorbs a bit of the light and reflects off all sides and it has an illusion in a different part of the cup. It reflects into the water and then you can see a little picture of it in the corner.

Here Paul seems confused but does grope toward applying his idea of an image (illusion) to the problem. He locates this image somewhere in the container instead of in the observer's eye, and attributes this displacement to the water. Perhaps he has in mind that the water is acting like some type of reflector or lens.

What Happens to the Light From the Flashlight After it Hits the Objects?

Paul's drawings of how the light behaves when it contacts the four different surfaces are fairly similar to each other. The mirror has one ray reflecting back, as does the frosted glass and the white wood. The frosted glass

Paul's Ideas After Instructional Intervention

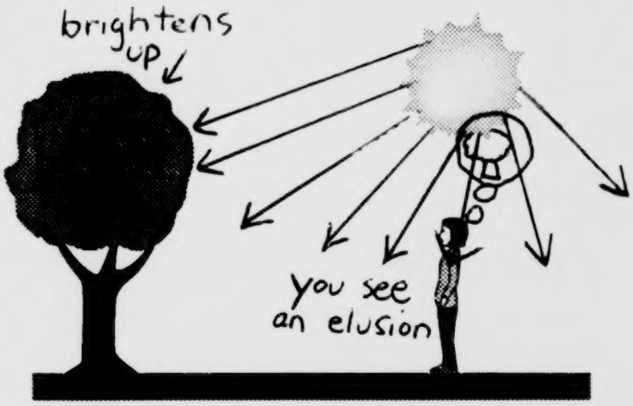
brightens up
you see an elusion

Diagram 12: *Draw arrows to show how light from the sun helps the girl to see objects.*

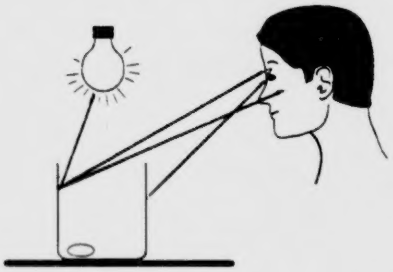

Diagram 13: *Why can't John see the penny in the bucket?*

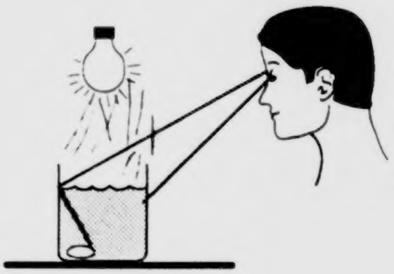

Diagram 14: *Why can John see the penny after the bucket is filled with water?*

also has several very faint lines emerging out the opposite side. The clear glass has one ray going through the glass. All four pictures include a "blob" of light at the point of contact. There is no written explanation for any of the four surfaces. Paul's explanations of what happens to the light after it contacts the surfaces are basically correct. His blobs of light are perceptually based. They are analogous to the splashes of light on his pre-evaluation and signify the circle of light from the flashlight visible on each surface.

In his post-interview, Paul gives answers consistent with his post-evaluation. When the light is shone on the mirror, "None goes through. Some might stay in. And most of it reflects back." For the translucent plastic, "A bit might stay in, the rest goes through." In the case of the transparent plastic, "It all goes through, except maybe for a couple of scratches. Three-quarters and one-fourth." Finally, for the white wood, "It just shows where the light is." The light "stays there". "A bit" reflects off, but "most of it stays there." Paul knows that very little light reflects off because if a lot was reflecting off, he could hold a mirror there and then "you might be able to see the reflection of this (the wood) in there." However, "It doesn't look like it's reflecting." Again Peter's explanation for seeing the circle of light on the surfaces is that the light "stays there". It does not occur to him that the flashlight emits a constant stream of light; what he sees on the surface is a "permanent" blob of light. Paul reveals that his test for reflected light is visibility, that is, if any light is reflecting off he will be able to catch it with a mirror. Paul still closely associates the phenomenon of reflection with a mirror.

Why Does a Black Object Look Darker Than a Gray Object?

On his post-evaluation, Paul leaves blank this question of why a black object looks darker to us than a gray object. No information is forthcoming from the post-interview either because the researcher forgot to include the question in the interview.

What Does the Coloured Glass Do to the White Light Shone Through It?

Paul selects the answer, "The glass lets all the light through but stops all the colours except red", from the options on the post-evaluation. The scientific answer to this question is, "The glass lets red light through, but it stops all the other colours". At first, these two answers may seem very similar but Paul's answer has one serious omission. His answer leaves out the answer to the question of where the red comes from. It seems that with his answer Paul is still implying that the red comes from the glass, even though he has not selected one of the options which states this directly as he did in his pre-evaluation. It is possible that Paul may have selected his answer because he now grasps the idea that white light is a combination of colours and that red is in the white light, however, the scientific answer expresses this much more clearly. It could be concluded from the evaluation that Paul is gaining a better understanding of this phenomenon but he is still not clear on what happens.

Paul's answer on the post-interview, however, resolves the question of how much he understands.

> Paul: The white light carries all colours and then it absorbs all the colours and just lets through red.
>
> Researcher: So the transparency absorbs all colours and only lets through the red?
>
> Paul: Yeah, okay. The transparency only lets through red light.

Now it is clear that Paul does understand this phenomenon. His answer is precise and scientific. Perhaps he had trouble selecting the right answer on the post-evaluation because of the apparent similarity between two of the alternatives. (Note: When the researcher was first examining this question and the possible answers given, he had difficulty seeing any difference, except in phrasing, between the answer Paul selected and the scientific answer.)

What Colour Will a Green Plant Look in Green Light?

Paul writes on his post-evaluation that the plant will appear "green because the light is green and it's green." In the post-interview he gives the same response with a bit of an explanation tacked on: "Because the green light shining on the green, that would make green. Green plus green is green." At this point it seems he still believes that colours of pigment and colours of light mix, that is, "Green plus green is green".

What Colour will the Red Pot Look in Green Light?

Paul anticipates this question in his answer to the previous question: "The holder would be black." He also answers it again in the space provided: "It would appear black." He adds no explanation. In the post-interview, he is also asked for an explanation.

> Researcher: Now what if we had a red pot and we shone a green light on it and there was (sic) no other light sources in the room. What colour would the red pot look to your eye?
>
> Paul: Black.
>
> Researcher: Why would it look black?
>
> Paul: Because green light and red mix to black.
>
> Researcher: Green and red mix to make black?
>
> Paul: Yes.

Now it is clear that Paul still does hold to the "mixing" theory. It is interesting to note that he gives the theoretically correct answer when naming the colour, most likely because he remembers his observations during the colour experiments. However, he then proceeds to give an explanation for the colour which is scientifically incorrect.

Why Does the Blue Book Appear Blue?

Paul answers on his post-evaluation that "the book reflects blue light and absorbs other colours." This is scientifically correct and different from his pre-evaluation where he stated that "The light helps our eyes to see the blue colour of the book." In the post-interview he gives an answer consistent with the above.

> Paul: White light, again, pours right into it, and only lets one colour stand out.
>
> Researcher: Stand out? And what is that one colour?
>
> Paul: Blue.

Again, this is a scientifically correct answer to the question, and is different from the essentially "illumination" view which Paul held to before intervention.

Why Are There Only Three Primary Colours of Light? What Are They?

Paul suggests on his post-evaluation that there are only three primary colours of light "because they all mix into the three colours." He writes that the colours are "black, white (crossed out) and I don't know the other two." In his post-interview he says the same: "Cause all colours mix into those three." Again, he suggests that two of the colours are "black, white and I'm not sure of the third one." Instead of suggesting that there are only three primary colours because all other colours can be made from them, an answer given by the vast majority of the other students who are probably applying their knowledge of mixing paints, Paul gives an answer which is the "reverse". He suggests, instead, that all colours mix into the primary colours. This makes his choice of colours and his inability to name a third colour very logical, that is, white is all colours, black is the absence of colour. Paul's thinking here is quite logical and apparently scientifically based on a knowledge of the nature of black and white, even though what he says is not the scientific answer to the question.

Cari's Ideas After Intervention

Cari's ideas after intervention are taken from her post-evaluation, her journal, and her post-interview.

How Does Light Help Us to See Objects?

Cari writes on her post-evaluation, "Cause if light was not there we would just see black." She has either gone back to a straight illumination theory or else is not interested in making any further explanation of her thinking. She makes no mention of rays, reflection, or the eye, all of which she wrote about on her pre-evaluation. In her diagram, however, she draws one ray of light traveling from the sun to the tree, then reflecting to the observer's eyes (Diagram 15). This is exactly the same as on her pre-evaluation. In her journal she writes, "No change". During her post-interview, she first points out that the light in the room comes from the lights and the windows. She then tells how we see.

Researcher: How does the light help us see, say, Matt's desk there?

Cari: Because the light reflects off his desk and then in your eyes.

This answer is quite different from her pre-interview where she presented an illumination theory of seeing, that is, "The light lights up the object and you see it." She seems here to have moved more toward a reflection theory of seeing. However, she does not mention an image. Perhaps the difference in her answers on this question can be attributed to an ability to express her thinking better in speech than in writing or, perhaps, she is still unclear on what her thinking is.

Why Can John Not See the Penny in the Bucket?

On her post-evaluation, Cari simply draws a line from John's eye just across the top of the near edge of the bucket almost to the far side of the bucket (Diagram 16). This line clearly misses the penny in the bottom of the bucket. She also draws short lines emitting from the light-bulb. There is no written explanation to accompany her diagram. In the pre-evaluation she had mentioned that if John looks "straight" he misses the penny, and also had added a comment about a shadow.

Cari's comments in the post-interview clarify her thinking on this question.

> Researcher: Okay, now why can't you see it at this moment?
>
> Cari: Because this (the side) is in the way.
>
> Researcher: What's it in the way of?
>
> Cari: Me seeing the penny. Like I see straight and this right here is in the way.

Cari expresses a "visual rays" type of understanding here which is consistent with her diagram. There is a "line of sight" from her eye, which is blocked by the side of the container.

Why Can John See the Penny After the Bucket is Filled With Water?

Now Cari draws rays from the lightbulb, one of which reaches the penny (Diagram 17). She also draws one ray from John's eye, through the side of the container, to the penny. There is no written explanation to give clues to her thinking but beside exactly the same diagram on her pre-evaluation she had written that "the water reflects light to the penny".

In her post-interview Cari is unsure of what is going on but attempts an explanation.

> Researcher: Why can you see the penny now, after I pour the water in?

Cari's Ideas After Instructional Intervention

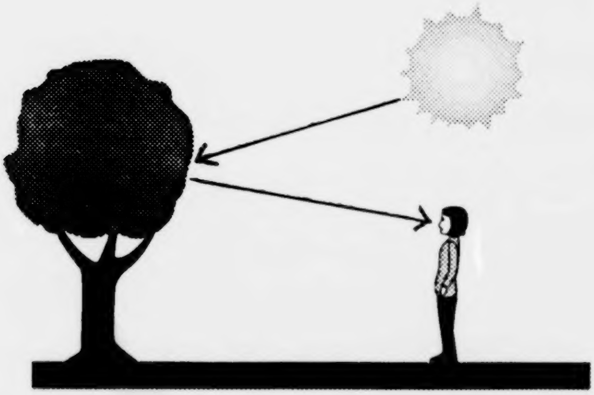

Diagram 15: *Draw arrows to show how light from the sun helps the girl to see objects.*

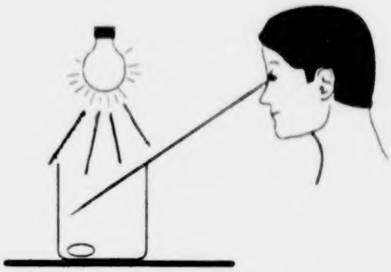

Diagram 16: *Why can't John see the penny in the bucket?*

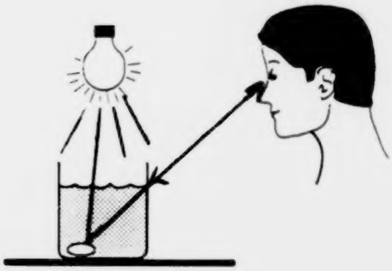

Diagram 17: *Why can John see the penny after the bucket is filled with water?*

Cari: I don't know. It reflects off the water, or something.

Researcher: What does?

Cari: The penny. Like the light comes and it reflects off the water and so does, like, I don't know. Then, I don't know. When you pour it in it looks like it's moving out and then you can see it. I don't know.

Researcher: Like it's slowly coming into view?

Cari: Yeah.

Researcher: Can you explain it in terms of light?

Cari: Maybe the light, I don't know. I don't know, the water makes it bigger or something, I don't know.

Researcher: Like magnifying?

Cari: Yeah.

Cari is making a valiant attempt to put forth ideas which might account for the penny "coming into view" but she is really not sure what is going on. She mentions reflection and magnification as possibilities. She had suggested reflection in her pre-interview but magnification is a new idea.

What Happens to the Light From the Flashlight After it Hits the Objects?

Cari's diagrams are very clear and almost completely correct. She draws the light rays reflecting from the mirror, both reflecting and passing through the translucent glass, passing through the clear glass, and scattering off the white wood. Actually, had she made the rays scatter off the translucent glass, she would have been completely correct. The biggest change in her thinking is in regards to the white wood where previously she had drawn the rays "staying on" the white wood and not reflecting off at all.

In her post-interview, Cari gives very similar answers for the first three objects. The light reflects off the mirror, most of the light goes through the translucent plastic but some "rebounds off", and the light all goes through the clear plastic. However, in the case of the white wood, she goes back to the "stays on" idea she presented on her pre-evaluation.

> Researcher: And what happens when I shine the flashlight on this white wood?
>
> Cari: I don't know. It doesn't reflect. It just stays there. I don't know. It doesn't look like it reflects.
>
> Researcher: How would you know if it did reflect? What would tell you that it was reflecting.
>
> Cari: If you were in a dark room you could tell.
>
> Researcher: How could you tell?
>
> Cari: Because it, we could put another board here, then if it, you could see it, or something. Like if it, then it would, rebound straight off you. Like put a board there and see if any light hits it. You could.
>
> Researcher: So if the light was reflecting you would see the light?
>
> Cari: If it was a dark room. If there's no other light.

Cari says that the light doesn't reflect, it "stays there". Her evidence for this statement is no doubt observation of the circle of light "on the board". Cari further reasons that if light is bouncing off the wood, she will see some evidence of the reflected light. Without perceptual evidence, she is unwilling to accept the idea of reflection. However, she also inserts several "I don't know's" among her remarks. Maybe she remembers the theoretical presentation where it was stated that light does reflect off objects and is perhaps uncomfortable with the discrepancy between what she concludes from the empirical evidence and what was stated by the "authority", that is, the researcher.

Why Does a Black Object Look Darker Than a Gray Object?

Cari's answer on the post-evaluation is that "Black absorbs all colours and grey reflects some colour." This answer is scientifically correct. It is also in essence the same answer as she gave on her pre-evaluation, which was, "Gray does not attract as much light as black does". Now, however she is stating her idea more clearly and scientifically, for example, by using the word "absorb" in place of the word "attract".

Cari's post-interview explanation is an even better statement of scientific thinking.

> Cari: Because black, I don't know. The grey absorbs some and then reflects some. The black absorbs all the colour.
>
> Researcher: All the colour?
>
> Cari: Yeah.

This is an even better answer because it also mentions reflection. Again, Cari has a clear understanding of this phenomenon. (Note: The researcher's probe is to see if Cari remembers the classroom discussion of a question raised by a student, that is, "If we see by reflection and black absorbs all light, how can we see black?" The scientific answer given in class is that the statement, "black absorbs all light" assumes an ideal black body which does not exist. Theoretically, a black body would be invisible, but in reality black objects do reflect some light and hence we can see them.)

What Does the Coloured Glass Do to the White Light Shone Through It?

Cari selects the answer, "The glass adds red colour to the light", on her post-evaluation. Her ideas have not changed from her pre-evaluation. She still feels that colour is something added to pure, colourless white light.

In her post-interview, however, her answer is totally different.

> Cari: It (the transparency) just lets the red light through.

Researcher: And what does it do to the other light?

Cari: I guess it absorbs all the other colours and then lets the red go through.

It is difficult to understand why Cari gives one answer on the post-evaluation, and then the opposite, scientifically correct answer in the interview. Perhaps her thinking is just inconsistent. Perhaps it is the test. Or, perhaps, the actual demonstration during the interview triggered her memory and caused her to recall the experiments and discussions focussing around the scientific explanation.

What Colour Will the Green Plant Appear in Green Light?

Cari writes on her post-evaluation that the plant will appear "Green because the green light won't affect the colour of the plant." In her post-interview, she says the same thing but also explains.

Researcher: If you have a green light shining on a green plant, what colour will the plant be?

Cari: Green.

Researcher: Why?

Cari: Because the green light won't affect the green plant.

Researcher: What do you mean?

Cari: Like we have white light and it doesn't affect, it doesn't change anything in the plant.

Researcher: You mean, doesn't change the way it would look under white light? Is that what you're trying to say?

Cari: Yeah, because it's green and green.

Cari still adheres to the "mixing" theory of colour. For her, green light plus a green plant equals green. This is what she means, in both cases, when she states that the green light won't "affect" the plant.

What Colour Will the Red Pot Appear in Green Light?

Cari's post-evaluation answer is very clear. The pot will appear "Black because the pot is red and the light is green and green and red make black." This is totally consistent with her "mixing" view of the green plant in green light. It is also consistent with her response in the pre-evaluation, except at that time she did not have the advantage of having actually tried green and red together and so at that time suggested the mix would result in "purple".

Cari's post-interview response to the same question is more confirmation of her "mixing" theory.

> Researcher: If we looked at a red pot under a green light, what colour would the red pot look?
>
> Cari: Black.
>
> Researcher: Why would it look black?
>
> Cari: Because the green and the red mix, kind of. They mix colours and green and red would make black.

It is interesting to note that during the small group experiments with colour, Cari insisted that green plus red looked dark, dark green and very much resisted the suggestion that it looked black. Now she is stating that green plus red does look black, however, she is still giving her observation the same interpretation that she gave her observation of "dark, dark green", namely, that it represents evidence for a "mixing" theory of coloured light and coloured objects.

Why Does a Blue Book Appear Blue?

Cari selects the scientific answer on her post-evaluation, that is, the blue book appears blue because "the book absorbs blue light and reflects other colours". This is a change from her pre-evaluation when she opted for, "the light helps our eyes to see the blue colour of the book", a basically "illumination" theory of colour.

In her post-interview, Cari gives the same scientific explanation.

Cari: Because it would reflect some colours and absorb some colours.

Researcher: What colours would it reflect?

Cari: I don't know, whatever colours make blue. And then the rest would absorb.

Although her understanding of why the book appears blue is certainly new, Cari makes no new entry in her journal regarding why objects appear coloured when we look at them. Possibly she was not interested in doing so, or possibly she was unable to generalize from the specific example of the blue book to all other objects.

Why Are There Only Three Primary Colours of Light? What Are They?

Cari writes on her post-evaluation that there are only three primary colours "because you can mix the primary colours and make any colour". This is the same answer she gave on her pre-evaluation. She guesses that the three primary colours are yellow, red, and blue which are the three primary colours of pigments.

In her post-interview, Cari presents the same ideas and the same conclusion.

Cari: Cause there are those three. If you take these two, mix them, you can make a colour and you can make a different colour. Those you can make, like, you can make all the colours just by mixing those.

Researcher: I see. What are those three primary colours? Can you name them?

Cari: I had it before. Blue, yellow, and red.

DISCUSSION OF ALL RESPONSES

Overall, more students held scientific conceptions of how we see and why objects appear coloured at the end of the instructional intervention than before it. This suggests that the intervention played some role in helping the students achieve a more scientific understanding. It must again be emphasized, however, that the key word here is "understanding". As previously stated, the rationale behind the "spontaneous conceptions" approach to instruction was that such an approach would provide a better understanding of scientific conceptions of natural phenomena. In this regard the evaluation questions which called for students to apply their theoretical conception to new problems played an important role. While a large number of students were able to state the scientific reflection theory of colour, only three were able to apply their theoretical knowledge to the penny problem so as to give a scientific explanation of why John was able to see the penny after the bucket was filled with water. At the start of the study no students were able to scientifically solve the penny problem. The same situation was apparent with respect to the students' conceptions of why objects appear coloured when we look at them. There was a great increase in the number of students who could state the scientific reflection theory of colour. Of these, only a minority were able to apply that theory to scientifically solve the problem of the red pot in green light. At the start of the study no students were able to scientifically solve the red pot problem. If our aim is to increase students' understanding there must be an emphasis placed on solving problems which require such understanding. There must be ample opportunity in both teaching and evaluation for students to transfer and apply their knowledge to new situations and new problems.

A large number of students changed their conceptions only partially while some did not seem to change theirs at all. "Complete" reconceptualization, then, is not easy to achieve, if by this we mean bringing students from their spontaneous conceptions to scientific conceptions. Spontaneous conceptions tend to be strongly held. Of course, no reconceptualization can ever be complete in the absolute sense, otherwise learning comes to an end. However, even those who did not change their overall conceptions thought about them, debated them, and attempted to test them. Perhaps a better way of looking at the aims of the instruction might be to look at reconceptualization as a long-term strategic goal and to look at thinking, discussing, and testing as the processes to come closer to such a goal. The use of these processes by the students involves learning in and of itself. Students become more familiar with science and how to "do it", as well as attaining a better understanding of scientific conceptions. The advantage to students becoming more familiar with science and how to do it is that it empowers them to go beyond the classroom in their learning. They begin on their own to ask questions about natural phenomena, to investigate them, and to try to explain them. One student went home and tried to make his bathroom dark as a means of figuring out how we see objects. This may be a better measure of his gains in understanding than his correct description of a scientific theory on a paper and pencil test. What is important for teaching and learning is to work out ways through which both how to do science and a better understanding of natural phenomena can be encouraged and evaluated in the classroom.

CHAPTER 6
CONCLUSIONS

The main purpose of this study was to examine an approach to science instruction which aims chiefly for understanding and which begins specifically from students' spontaneous conceptions about natural phenomena. There are ten major conclusions which emerge from this study. Each of them will be discussed separately. However, the conclusions drawn form an integral whole and should be looked at in the context of that whole.

Students have spontaneous conceptions about natural phenomena which they bring to science instruction.

This study shows, just as numerous previous studies in many areas of science have shown, that students have spontaneous conceptions about natural phenomena. These conceptions are explanations or partial explanations for these natural phenomena. In this study, the students were shown to have spontaneous conceptions about optics. Before the instructional intervention, students were evaluated as to their ideas about light and colour. Specifically, they were asked about their conceptions of how we see objects and of why objects appear coloured when we look at them. On their pre-evaluations, in their journals, and in their interviews, students presented ideas which constituted explanations for these phenomena. Their explanations differed from student to student to some extent in wording, in systematicity, and in essence, but over-all they displayed more similarity than difference. These conceptions were not just "wild guesses" but were clearly developed by the students to explain how we see and why objects appear coloured. It must be concluded, then, that students held to these conceptions at the start of the instructional intervention and that they came to instruction, not tabula rasa, but with preconceived explanations of natural phenomena. Further, it must be assumed that these conceptions were not immediately discarded when the instruction commenced. The spontaneous conceptions of the students influenced the manner in which the students interacted with the instruction. They were, to some degree, the "lens" through which the students viewed the ideas and experiences presented during the instruction.

Students' spontaneous conceptions generally differ from scientific theories.

The spontaneous conceptions of the students about how we see and about why objects appear coloured were found, in almost all cases, to differ markedly from scientific theories. The pre-evaluations, first journal entries, and pre-interviews provided enough information about students' conceptions to indicate that the students held to neither a reflection theory of seeing nor to a reflection theory of colour. On the contrary, almost all students conceived of seeing as an act directed toward an object which was illuminated by light. No students made references to images although some did mention reflection to the observer's eye. Almost all students initially conceived of colour as an innate property of the object and of light as something which illuminates the object so the observer can see the colour. Few students made reference to the absorption and/or reflection of light. Further, those students who did seem to have some sense of scientific theories of seeing and of colour had great difficulty in transferring the general theories to clarify specific problems. Only three students were able to solve the problem of the penny in the bucket and only seven students were able to solve the problem of the red pot in green light. In other words, even those students who could give a more or less correct description of the scientific theory did not display the ability to apply the theories which would indicate a deeper understanding.

Students' spontaneous conceptions can provide a starting point for science instruction.

The rationale for the study was to try to develop an approach to science instruction which would give students a better understanding of natural phenomena. This understanding was conceived of as a type of learning which went beyond memorization. It was assumed that one of the main barriers to this understanding might be the existence of students' spontaneous conceptions about natural phenomena which would cause them to assimilate further instruction into their spontaneous conceptions rather than to alter their conceptions in light of the instruction. Thus, the first step in the instruction was to uncover students' spontaneous conceptions and to make the students aware of them. This was done through discussion in small groups and in the whole class. These spontaneous conceptions, then, provided the starting point for instruction. The use of this starting point contrasted with traditional formal instruction which appears to base itself on the implicit assumption that students come to science instruction "tabula rasa", or, that if students do have initial ideas these ideas will not be influential in determining how the student interacts with the new learning. In traditional formal instruction, then, the starting point for instruction is the content and process of the science to be taught rather than the students' initial ideas. In the approach to instruction tried in the study, the students were first encouraged to consider their own ideas, then to move from this to consideration of scientific ideas as a possible alternative. Their later understanding was, to some extent, constructed on the basis of their initial conceptions.

Students' spontaneous conceptions have parallels with the history of science.

It was found in the study that the spontaneous conceptions of the students had some parallels with the history of science. This was not a one-to-one correspondence in the sense that the development of student ideas recapitulated the history of science. However, a study of the history of ideas in optics, specifically of theories of vision and colour, and a comparison of this history with the ideas displayed by the students, showed that students' theories were often similar to historical ideas. For example, in their attempts to understand seeing, the Ancients concerned themselves primarily with the question of what happened between the object and the eye. One theory offered by certain ancient thinkers was that something traveled from the eye to the object. Similar ideas were found to be held by some students who suggested that the eye "looked at" the object. The nature of this student conception became especially clear when solutions were presented for the penny problem. A number of students explained that the side of the container blocked the observer's "view". Further, until the time of Grimaldi (17th century), theories of colour assumed that colour was an inherent property of objects rather than the result of the interaction of light and the pigment of the object. The majority of students held a similar conception of colour. Again, the nature of this conception became particularly clear when students were asked to solve the problem of the red pot in the green light. The similarity of students' ideas with the history of science suggests that the history of science may provide assistance in predicting what spontaneous conceptions the students may hold before instruction. A knowledge of the historical development of ideas about natural phenomena in a domain may be good preparation for teaching students in that domain if the teacher plans to start from students' spontaneous conceptions. Although some type of pre-evaluation or interviewing is obviously the best way to discover students' spontaneous conceptions, the history of science can be a useful adjunct to such preliminary work.

Students' spontaneous conceptions are not easily altered by instruction.

The instructional intervention revealed that the spontaneous conceptions of the students were not easily altered by instruction. Spontaneous conceptions had certain characteristics. First, the conceptions were strongly and intelligently held. When faced with contradictory evidence, students often tried to maintain their conceptions and to explain the evidence in terms of their held conceptions. For example, when faced with the evidence that a red object appears black under green light, many students were unwilling to accept the scientific explanation that the appearance of black was due to the absorption of green light by the object. Instead, the students attempted to retain their conception of colour as an inherent property of objects by explaining the appearance of black as the result of a "mixing" of the green colour of the light and the red colour of the object. In Piagetian terms, the students tried to assimilate the evidence rather than to accommodate it. Second, the students' conceptions were not isolated facts but were part of a larger grouping of concepts. To alter student conceptions requires instruction which takes into account various subsidiary assumptions. For example, when the students were told of the image which falls on the retina, they still tended to speak and write in terms of "seeing" the image. The idea of the image was incorporated with the idea of "seeing" as an act directed at an object, rather than viewed in terms of the reception of light by the eye. Third, students' spontaneous conceptions are not systematized in the same sense that a scientific theory might be systematized. Ideas which would be considered contradictory in a scientific theory can coexist in the students' spontaneous conceptions. For example, many of the students were able to hold a reflection theory of light and an inherent theory of colour, or, a reflection theory of colour with an illumination theory of light. Scientifically, however, such a coexistence is contradictory, since a reflection theory of seeing implies a reflection theory of colour and vice versa.

Students' spontaneous conceptions can be altered by instruction.

Although students' spontaneous conceptions are not easily altered, some of their conceptions did undergo change. It is assumed that these changes can be attributed to the instructional intervention. Evidence for the changes in students' conceptions can be found in the process of change as well as in the products of change. For example, analysis of the student journals, the whole class discussions, and the small group discussion of the interview group, shows numerous examples of students' thinking about their ideas; considering their ideas in light of new evidence; questioning their spontaneous conceptions, the conceptions of other students, and the scientific conceptions presented by the researcher; revising their ideas; and presenting conceptions differing from those that they held before the instruction. Sometimes changes in student conceptions moved them further away from the scientific conception but, in general, progress was made toward more scientific conceptions. Certainly not all students ended up with a deep understanding of scientific conceptions but this result was never felt to be a measure of the success of the instructional intervention. The general aim of the study was to bring about a better over-all understanding for the group as a whole, not necessarily a deep scientific understanding for every individual student.

The instructional intervention used in the study can help students gain a better understanding of scientific conceptions.

For the purposes of the study, a distinction was drawn between learning as memorization and learning as understanding. Although such a characterization represents two extremes, the type of learning aimed for in the study was to be more understanding than memorization. It was hoped that students would not simply write down the scientific conception on the grounds that it was the "right answer". Emphasis was placed in the study on learning by active participation rather than passive memorization. Emphasis was also placed on evaluation of the process of learning as well as the products of learning. Evidence that students were developing a deeper understanding during the process of learning was based on analysis of the journal entries, the whole class discussions, and the small group discussions of the interview group. It was concluded that, on the balance, the evidence showed that students were attempting to develop understanding rather to memorize ideas as facts. This evidence in support of understanding as the main goal was provided by the fact that some students did not change their ideas to the scientific conception as well as the fact that some students did change their ideas, either to a better understanding or to the scientific conception. In other words, the fact that some students did not change their conceptions showed that the "authority" of the researcher was not sufficient grounds for them to give the "right answer". One student even specifically noted on her post-evaluation that one version of her diagram represented the "teacher's idea" while the other version represented "my idea". Evidence that students were developing a deeper understanding in terms of the products of the learning was based on the fact that a few students were not only able to articulate the scientific conception but were also able to transfer and apply it to solve new and unfamiliar problems. For example, some students were able to apply the scientific conception of reflection to one or both of the penny problem and the red pot problem.

The instructional intervention used in the study can empower students to learn on their own.

Classroom time for learning is always limited. Many educators have mentioned the "time press" in education as a factor which mitigates against learning. It has been suggested that there is too much "coverage" in education and not enough retention, and that this contributes to the preponderance of memorization over understanding as a mode of learning. Assuming that classroom time will always be limited in terms of the duties and obligations of teachers, one of the ways out of this dilemma is to encourage students to learn outside of class time. In this sense, learning becomes an ongoing activity rather than something limited to schools. The study experienced some success in encouraging students to learn outside of the allotted classroom time. This was seen, for example, when a number of students referred to experimental investigations which they attempted at home. Several students spoke of darkening rooms to test their theories of seeing. Other students brought back answers to questions raised by their fellow students. Students also approached the researcher before and after sessions in order to initiate or continue discussion on the issues being raised during the study. An attitude which considers learning as important outside allotted class time is most likely developed by the nature of the learning which takes place in the classroom. In other words, if students become convinced that the learning they are doing in the classroom is relevant and interesting, they will continue it outside of class time. It should be noted that "relevant and interesting" refer not only to the content of the learning but also to the nature of the learning, that is, to the manner in which the learning is approached. If students are empowered to take an active role in classroom learning, rather than a passive one, they will be more likely to continue to learn outside the allotted class time.

The instructional intervention used in the study can help students understand the nature of science.

The approach to learning developed in the study is based on a view of science as explanation. This might be contrasted to other views of science, such as science as facts, rules, and definitions, or science as process skills. Again, the question here is not one of "either or" but of emphasis. Facts and process skills are both important to science The question is how to best approach them so students gain a better understanding of them, that is, how to "do" science so students not only gain a better grasp of science content and process but also a better grasp of the nature of science itself. Again, it is thought that if such an approach can be developed, students will be empowered to go beyond the immediate classroom learning and to become "more scientific" in their overall thinking. By participating in instruction based on beginning with students' conceptions, testing them, and then considering other possible explanations for the phenomena under investigation, students can develop an understanding of scientific knowledge as testable, as corrigible, and as progressive in its general development. In other words, science involves a process of increasing understanding rather than a memorization of static universals. The view of science which it is hoped the type of instruction used in the study will encourage is best summed up by one of the prefatory quotes to the thesis: "Knowledge is the reflection of nature by man. But this is not a simple, not an immediate, not a complete reflection, but the process of series of abstractions, the formation and development of concepts, laws, etc., embrace conditionally, approximately, the universal law-governed character of eternally moving and developing nature" (Lenin, in Naletov, 1984, p. 402).

Reconceptualization takes a long period of time.

An important point made in much of the literature on spontaneous conceptions is that reconceptualization may take a long period of time. In other words, it may take a long time for students to change their spontaneous conceptions. In general, then, the process of coming to an understanding of natural phenomena is not something which will occur in a few lessons. This study supports this conclusion. Although some students did reach an understanding of the scientific theories of seeing and colour, as manifested, for example, in their ability to transfer and apply the scientific conception to solve problems, the majority of students did not. At the same time, the overall trend of the class was toward a better understanding. This was especially noticeable after an analysis of the data sources which tried to keep track of the process of student learning. This need for a long period of reconceptualization is not surprising, given that students' spontaneous conceptions tend to be strongly and intelligently held. Further, students, when being taught in a manner which emphasizes understanding, will tend not to accept a new conception until they are satisfied that it is a better explanation for the phenomena under investigation than the conception previously held. Since their spontaneous conceptions are often based on their immediate experience, observations and perceptions, and scientific theories are often abstract and involve transobservational concepts, this makes the task of comprehensive reconceptualization even more difficult.

CHAPTER 7
IMPLICATIONS

TEACHING SCIENCE

Given that teaching for understanding is a desirable goal in science instruction, it is important to develop teaching approaches which can bring it about. Science instruction which takes into account students' spontaneous conceptions and uses them as the instructional starting point is a promising approach. Basically, it involves finding out what students' spontaneous conceptions are through pre-evaluations, having students discuss their spontaneous conceptions, having students test their conceptions, having students examine their conceptions in light of the evidence gathered from their testing, and attempting to bring students to a more scientific understanding. The diagnosis of students' spontaneous conceptions can be accomplished through paper and pencil evaluations, interviews, and informal questioning. Once the conceptions have been determined, they are summarized and brought to the students as possible theories for discussion. These discussions can be in the whole class or in small groups. After "deciding on" a theory or theories, students are asked to determine ways in which the explanatory power of their theory can be tested. This generally involves some type of experimentation. Students can then compare the results of their experiments with their initial ideas and see whether their experiments tend to corroborate or to challenge their ideas. Contradictions between experiment and their ideas may be used to help the students to achieve a more scientific understanding of the phenomena under investigation.

The above is merely a general outline of the approach to instruction. In order to help students achieve a better understanding, many other "pieces" need to be integrated with it. For example, it is important that the students carry out the discussion on their various theories in an appropriate manner. Guidelines such as presenting one's own ideas, listening seriously to other ideas, letting everyone air their views, and agreeing to disagree, are important if the discussion is to achieve its purpose. This, in turn, points to a classroom atmosphere where students feel comfortable in airing their views and are not afraid to be "wrong" or in the minority. Some knowledge of science content and processes is also necessary. Students will have difficulty investigating a topic they know nothing about. They will also have difficulty doing experiments if they do not have some knowledge of the required science processes. Content and process may be developed as the investigation progresses but it may be necessary to do preliminary work in these areas. Starting from students' spontaneous conceptions, then, does not constitute a magic formula which is complete in and of itself. However, it certainly could be an integral part of an approach to science instruction which enhances student understanding. It should be taken under serious consideration, put to use, and developed further in light of the results which it achieves.

The role of the teacher in instruction which takes students' spontaneous conceptions as its starting point may be best characterized as a balance between guiding and challenging. On the one hand, the teacher must assist students to move toward more scientific conceptions. The nature of scientific conceptions is that they are not derived directly from immediate experience but represent a long-term development of human knowledge over thousands of years. It is unlikely, then, that students will arrive at scientific conceptions on their own. Both the history of science and the study just completed demonstrate that more than one theory may be derived from the same sense data. On the other hand, if the teacher plays too much of a role, she will fall back right into the role of the traditional instructor, that of the "teller of knowledge". Unless the students participate actively and consciously in scientific investigations they will achieve little understanding, whether the investigations start from students' spontaneous conceptions or from the textbook. To achieve this balance between guiding and challenging the teacher must, for example, be good at listening, at probing, and at questioning. The teacher should have an adequate knowledge of the content and process of science. This does not mean the teacher must be an expert in all areas of science. Perhaps the best guideline is that the teacher be prepared to develop her understanding along with the understanding of her students. Being conscious of the development of her own understanding puts the teacher in the right frame of mind to help the students develop theirs. The question of how much challenging and how much guiding is not reducible to a formula but requires ongoing professional decisions on the part of the teacher as she interacts with her students.

If we are teaching for understanding we must try to develop some means of determining if our aims are being achieved. In this regard, attention should be paid to the process of learning as well as to the products of learning. Some of the methods used in the study to monitor the changes in students' ideas could prove useful. Individual response journals can be a daily record of the development of student understanding. They can also be a means of teaching students if the teacher responds to each student entry on a daily basis. The journals become ongoing dialogues between teacher and students because they provide a way in which the teacher can interact with the ideas of every student every day. The type of questions which students ask and answer also provides guidance as to how student understanding is developing. When students start to both ask and answer "higher level" questions, this is an indication that they are deeply involved in their learning and are seeking understanding. Taping discussions provides clues as to what issues are on students' minds and how they are dealing with them. It is unrealistic to expect that a classroom teacher could transcribe all sessions with all students but judicious use of this technique could be very useful. Small group work where the teacher interacts for a period of time with each group provides further clues to what students are thinking. Such interaction also provides a good opportunity for teachers to guide and challenge as the students pursue their investigations. The products of instruction can also be evaluated for understanding. Students can be tested to see if they can explain their new conceptions to other students in such a way that the other students can understand them. They can be tested to see if they are able to transfer and apply their conceptions to new and unfamiliar problems. Again, many of the above methods are not new but are pieces to integrate with the spontaneous conceptions approach to make it practical and useful in the classroom.

SCIENCE CURRICULUM

In general, science curricula are not designed to take into account the spontaneous conceptions of students. For example, *Exploring Science* (Blecha et al, 1979), a popular elementary science series, includes a unit entitled, "Light" (Green Book, Grade Five), which is further divided into three sub-sections, "Pathways of Light", "Colour", and "Seeing is More Than Looking". The teacher guide lists the main concepts for each sub-section at the bottom of pages 146, 158, and 168. Not one of these lists includes the scientific conception of how we see. The implication is that it is not an important idea. The research just completed shows that it is critical to students' understanding, not only of seeing but of colour. The scientific conception of how we see is finally listed at the end of the guide, under "Reviewing the Main Ideas" (p. 189), where it is fifth in the list. It is stated there as, "You are able to see because light bounces off things to your eyes." This after-the-fact listing further plays down the importance of this concept. Also, as we have seen in the study, this statement is so general that it can be interpreted as expressing an illumination conception of seeing just as easily as it can be interpreted as a reflection conception. The question of how we see is first specifically taken up on p. 146, where it is suggested that the most important reason you are able to see things is that "Light was shining on the things you saw". Again, this can easily be taken as a statement of illumination rather than reflection. The next mention of how we see is on p. 154, where it is mentioned under the subheading, "Bouncing light". The statement is made that "When light bounces off things and travels to your eyes, you are able to see". First, this statement is not emphasized, but is mentioned only in passing during a discussion of bouncing light. Second, it is easily interpreted in terms of an illumination theory of seeing, that is, once the object is illuminated then we can "look at it" and thus "see it". The critical question on which scientific understanding turns is whether or not the light which is reflected to the observer's eyes is illuminating the object or is an image of the object. Later, the guide describes the physiology of the eye and how the image is formed on the retina. But this is in a separate section on the eye, "Seeing is More Than Looking", and the function of the eye is not firmly connected to the role of reflected light. At the start of this section (p. 169), it is mentioned in passing that, "As said before, you see things because light bounces off them to your eyes". The first part of this section, "seeing the light", then continues for two pages on what happens to light inside the eye and concludes, "Once the message reaches your brain you are able to see" (p. 170). Again, this allows the student to conceive of seeing as some act separate from the reception of reflected light, that is, "seeing" is something which is "done" after the message from the optic nerve reaches the brain.

Research into spontaneous conceptions provides a basis for revising science curricula so as to specifically deal with students' spontaneous conceptions. If this is not done, program-makers run the risk that students will integrate the unit material into their spontaneous conceptions rather than accommodate their conceptions to the new learning. The revision of curricula, however, should include not only changes in the material and how it is presented in the textbooks but also guidelines as to instructional approaches which teachers can use with the material so as to bring about better student understanding. It is what teachers do with curriculum materials that is most important. On one hand, the *Exploring Science* unit could certainly be strengthened by a better presentation of and emphasis on the scientific conception of how we see, an improvement which could be made by taking into account students' spontaneous conceptions (Eaton, Anderson, and Smith, 1984). On the other hand, the manner in which the students interact with this presentation is of great importance in determining whether or not they will understand it. The aim of altering science units is not to make it easier for students to memorize the "right answer" but to make it easier for them to develop a better understanding of natural phenomena. As has been noted, this may mean that, after a unit on light, not all the students can articulate the scientific conception of how we see. However, if our "new" methods of evaluation are appropriate, it may be possible to determine that students have achieved a better understanding. As has been noted, research on students' spontaneous conceptions demonstrates that reconceptualization may take a long time. If we want this reconceptualization to involve understanding, we must be prepared to be patient and to allow students to actively participate in their learning.

TEACHER EDUCATION

Traditional formal science instruction usually teaches science as one or both of facts, rules and definitions, and/or process skills. Teacher education programs generally include these two approaches in their teacher training. A knowledge of science content and processes is desirable for the beginning science teacher. It would be absurd to attempt to teach science, at any level, while knowing nothing about it. But this scientific knowledge should be viewed as means to an end rather than as an end in and of itself. The two important questions in education are, "What should we teach?", and "How should we teach it?" Both content and process are important, but if we cannot teach so that children develop an understanding of what they are being taught, then our efforts to decide what content we should teach will be somewhat pointless. We may select our curriculum material with all the good intentions in the world but if we do not attend to the question of instruction, children will have to learn in spite of our attempts to educate them rather than because of them.

Practising science teachers should be made aware of research on spontaneous conceptions and its implications for science teaching. They should not be given the impression that it is a panacea in and of itself. Again, the existence of students' spontaneous conceptions and the fact that they interact with further instruction is just another in the continuing attempts to develop better approaches to science instruction. Practising teachers should also be made aware of the need for developing conditions for discussion, of the necessity for appropriate questioning, and of ways to assist students in conducting and interpreting experiments. Without such adjuncts, an awareness that students bring spontaneous conceptions to instruction is not useful. The critical task, then, is to help practising teachers grasp that a knowledge of students' spontaneous conceptions can be of assistance in teaching science for understanding. The fact that a student is developing understanding may mean that her knowledge is incomplete but such is the nature of all scientific knowledge. Spontaneous conceptions are not the faster route to the right answer, they are the slower route to a better understanding.

RESEARCH

Further research can and should be undertaken on the spontaneous conceptions approach to science education. It is important to consider the direction of such research. At present, the majority of research has focussed on the nature of students' spontaneous conceptions in a wide range of science areas. Hundreds of studies have been done in recent years which have summarized students' spontaneous conceptions in mechanics, earth and gravity, heat, photosynthesis, heredity, light, and so on. Most of these studies also include attempts to analyze the nature of spontaneous conceptions and to explain why students hold them. If research continues to remain focussed on the task of cataloguing and explaining students' spontaneous conceptions, it will confirm the suspicions of some that the main assumption behind such research is that the most important factor in science teaching is what children think, and that the development of human scientific knowledge over two thousand years is of secondary importance. The conclusion may be that education should be mainly concerned with what children think rather than with what we can teach them. Vygotsky (1962) noted that the interrelation of scientific and spontaneous concepts is a special case of the overall relationship between school instruction and the mental development of the child. The three approaches to mental development which Vygotsky saw as typical of his time were that learning depends on development and development is not affected by learning, that instruction and development are synonymous, and that instruction usually precedes development. (Vygotsky, 1962). Vygotsky upheld the latter position. In other words, Vygotsky gave instruction the primary role in education over development. Vygotsky concluded that without instruction, education becomes groping in the dark. Following Vygotsky, then, the main purpose of research in spontaneous conceptions in science should be to improve instruction, to serve as a means of helping educators develop approaches which can better teach science for understanding. The point of spontaneous conceptions research, then, is not to describe the world but to change it.

The research which has been done on instructional strategies which might lead students to a better understanding of natural phenomena is not large. Some work has been done in the area of conceptual change (Posner et al 1982, Shuell 1987, and Hashweh 1986, 1988), on the grounds that a movement from spontaneous conceptions to scientific conceptions involves conceptual change and thus an understanding of how conceptual change takes place is important to the development of appropriate instruction. The conceptual change literature comes mainly out of the discipline of cognitive psychology. Most researchers who mention conceptual change in their spontaneous conceptions research refer to Posner et al. as the source of their views. Some work has also been done in actually developing and trying out instructional strategies (Hewson 1981, Nussbaum and Novick 1982; Anderson et al. 1983, 1984, 1986a, 1986b, , and Minstrell 1986, 1989). In the development of instructional strategies, two strands seem evident. One is based mainly on the assumption that the primary task of instruction is to bring students from a spontaneous conception to a scientific conception. The second is based mainly on the assumption that the primary task of instruction is to help students develop a better understanding of natural phenomena. These are not hard and fast lines and they may at times coincide. The danger in too much emphasis on the first perspective is that the new approaches to instruction may merely make students better memorizers of scientific conceptions. The danger in too much emphasis on the latter approach is that it may lead to a neglect of scientific conceptions on the grounds that students are incapable of understanding them. But understanding of a scientific conception should not be looked at as something which occurs in a very short time and which is characterized by the student's ability to present a concise scientific description akin to that of a university professor or a practising scientist. Understanding a scientific conception is a long-term process, just as the development of human scientific knowledge has gone through and is still going through a series of better and better approximations, although with twists and turns, setbacks and leaps forward. Future research on instructional strategies, then, should keep both strands in mind. Its direction might be summed up as a continuing attempt to develop approaches to science instruction which help students to develop a better scientific understanding of natural phenomena. In this endeavor, the taking into account of students' spontaneous conceptions is an important piece of the puzzle.

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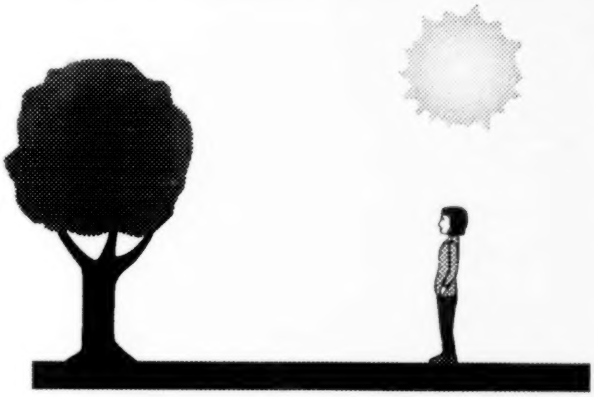
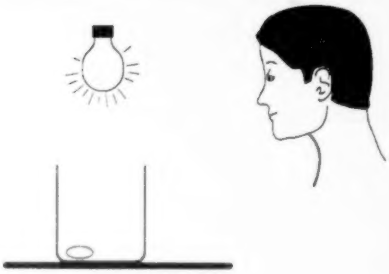
Appendix A
Seeing and Colour Research: Evaluation

1. How does light help us to see objects?

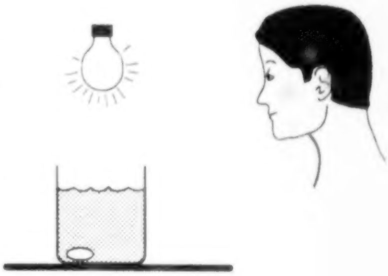
2. In the diagram to the right, the girl sees the tree. Draw arrows to show how the light from the sun helps her see the tree.



3. (i) John looks down into a bucket as shown. There is a penny on the bottom. John cannot see the penny. Explain why John cannot see the penny. Explain by drawing on the diagram if you like.

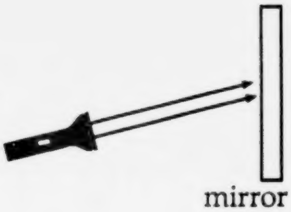


(ii) Now the bucket is filled with water. John can now see the whole penny even though he has not changed his position. The bucket is also in the same place as before. Explain why John can see the penny when the bucket has been filled with water. Explain by drawing on the diagram if you like.

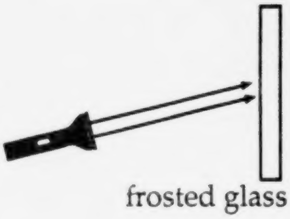


4. Draw arrows on the following pictures to show what would happen to light from the flashlight after the light hits the objects shown below. If you cannot draw arrows, explain in writing what happens.

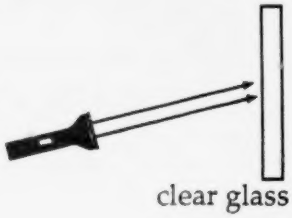
(i) A mirror



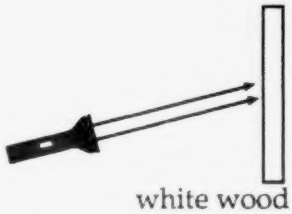
(ii) A piece of frosted (translucent) glass



(iii) A piece of clear (transparent) glass



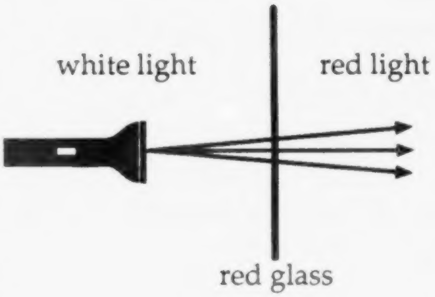
(iv) A piece of white wood



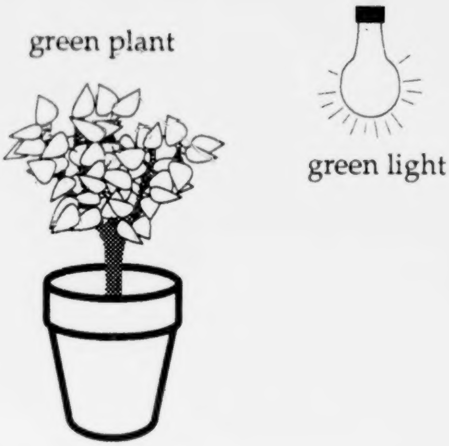
5. Why do you think a black object looks darker to us than a gray object?

6. When you shine a white light (from a flashlight, for example) through a piece of red glass, the light looks red on the other side of the glass. What does the red glass do to the light? Underline the best answer from the choices below:

(a) The glass adds red colour to the light.
(b) The glass lets all the light through, but stops all the colours except red.
(c) The glass lets red light through, but it stops all the other kinds of light.
(d) The glass turns the white light into red light.
(e) I don't know.



7. Green light is shining on a green plant in a red pot. There are no other lights in the room.
   (i) What colour will the green plant appear? Why?



   (ii) What colour will the red pot appear? Why?

8. When we see a blue book (underline the best answer from the choices below),
   (a) The light helps our eyes to see the blue colour of the book
   (b) The book absorbs blue light and reflects other colours
   (c) The book reflects blue light and absorbs other colours
   (d) I don't know.

9. Why are there only three primary colours of light and not some other number?

10. What are the three primary colours of light?

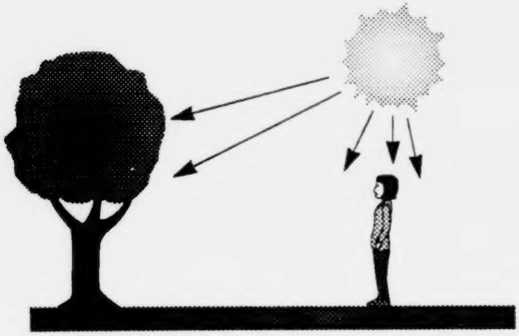
Journal Writing

In your journal, answer the following two questions as best you can. You may write, draw diagrams, or answer in any way that best expresses what you think. It does not matter how long or short your entry is; just do what is necessary to clearly explain your ideas. After each science class, you will be given time to make a further entry on each of the two questions. Each new entry may add to or be different from the previous entry or entries. In your journal writing, try to show the progress of change in your ideas on the two questions. The two questions to answer are:

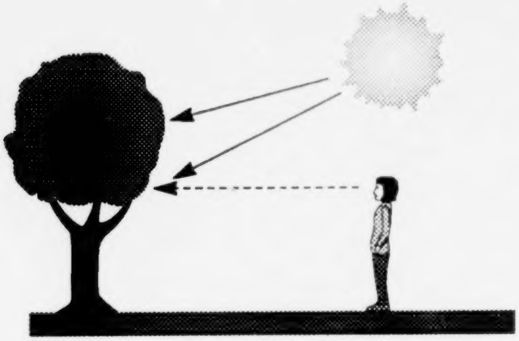
1. How do people see objects?
2. Why do objects appear coloured when we look at them?

Appendix B

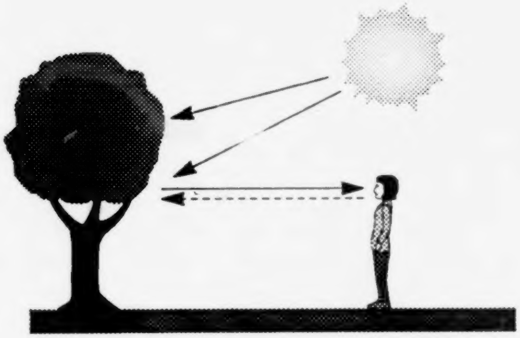
Spontaneous Conceptions of How We See from Pre-Evaluation (version 1)



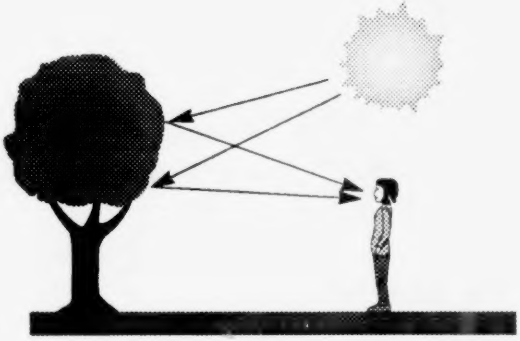
Illumination Theory
Light from the sun illuminates (lights up) what we want to see.



Visual Rays Theory
Light illuminates what we want to see and then our eyes "see" it (eyes to object).

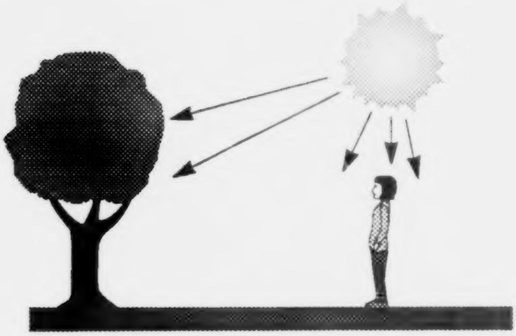


Two-Way Theory
Light illuminates what we want to see, light reflects to our eyes, our eyes "see" the object (eyes to object).

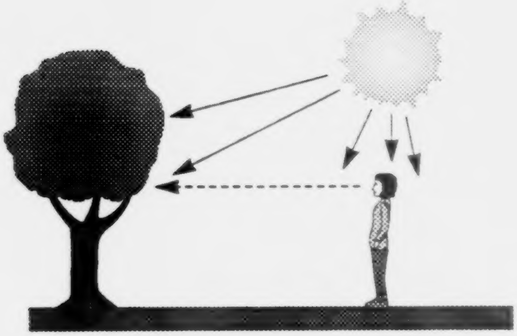


Reflection Theory
Light reflects from the object to our eyes, stimulating cells in our retina (back of the eye).

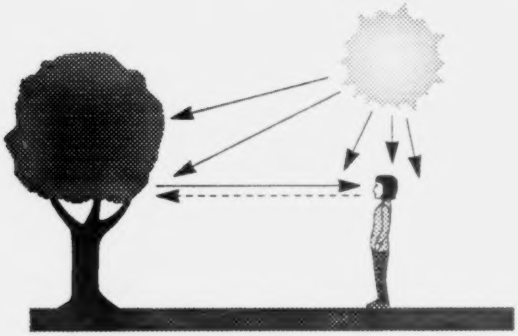
Spontaneous Conceptions of How We See from Pre-Evaluation (version 2)



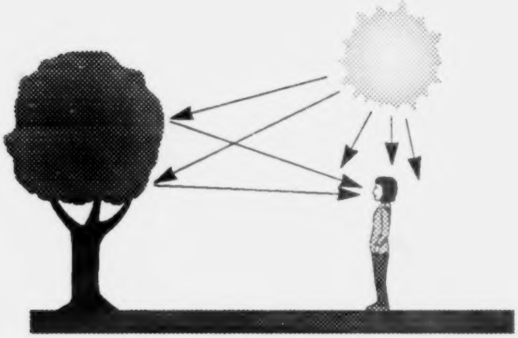
Illumination Theory
Light from the sun illuminates (lights up) what we want to see.



Visual Rays Theory
Light illuminates what we want to see and then our eyes "see" it (eyes to object).



Two-Way Theory
Light illuminates what we want to see, light reflects to our eyes, our eyes "see" the object (eyes to object).



Reflection Theory
Light reflects from the object to our eyes, stimulating cells in our retina (back of the eye).

APPENDIX C

THEORIES OF VISION AND COLOUR FROM ANTIQUITY TO KEPLER AND THOMAS YOUNG

GRAECO-ROMAN

"We have found the development of three theoretical lines of thought. First, that of the Pythagoreans who considered that rays emerged from the eye. Secondly, that of the Atomists who suggested that bodies emitted simulacra. Thirdly, that of the Platonic school which attempted to combine both the emissions. A fourth theory, which does not appear to have much following, although it was supported by Aristotle, considered vision as being the result of a movement between the object and the eye. The theory of the Pythagoreans seems to predominate and to have greater vitality than the others" (Ronchi, 1970, p. 36).

"The common premise of all ancient theories of vision was that there must be some form of contact between the object of vision and the visual organ, for only thus could an object stimulate or influence the visual power and be perceived. Now, in general there appeared to be three ways in which contact could be established. The object could send its image or ray through the intervening space to the eye; the eye could send forth a ray or power to the object; or contact could be established through a medium (usually air) that intervened between the object and the eye" (Lindberg, 1983, p. 339).

Intromission Theories:

Leucippus (5th C. B.C.):

We do not see objects but we see what the objects send to represent them, some image, shadow, or simulacrum which envelops the bodies and can detach itself from them in order to bring the shape, colour, and other qualities of the bodies they emanate from (Ronchi, 1970).

Democritus (c. 460-360 B.C.):

The air between the eye and the object receives an imprint as a result of the pressure exerted on it by the eye and the object. Objects continuously emit a substance which imprints itself on the eye (Ronchi, 1970).

Epicurus of Samos (342-270 B.C.):

Bodies constantly emit forms similar to themselves. These are called "eidola" or images. While being transmitted they retain the colour and form of the objects. They travel at great speed. These images impress on our senses (Ronchi, 1970).

Lucretius (c. 95 B.C.-c. 51 B.C.):

Lucretius supported Epicurus' concept of eidola (Ronchi, 1970).

Extromission Theories:

Empedocles (444 B.C.):

Seeing involves an intangible tentacle which reaches out from the eye and grabs the object being seen (Ronchi, 1970).

Archytas (a Pythagorean) (c. 430-305 B.C.):

Vision is due exclusively to an invisible fire which issues from the eyes to contact the objects and reveal their shape and colour (Ronchi, 1970).

Euclid (3rd C. B.C.):

The eye emits visual rays which travel out in a straight line, contact an object, and cause the sensation of sight. Radiation issues in the form of a cone and travels in straight lines. When it falls on an opaque object, that object is seen and the perception is somehow (unexplained) communicated to the eye. The eye, then, is the active participant in seeing.

(Note: Euclid makes no reference to the role of light) (Lindberg, 1976; Ronchi, 1970).

Hipparchus (c. 190-120 B.C.):

Rays emitted from a person's eyes go out and touch the object, bringing back the elements necessary to see the object (Ronchi, 1970).

Hero (62 A.D.):

Material rays proceed outward from our eyes (Lindberg, 1976).

Ptolemy (127-148 A.D.):

A material, visual flux extends conically from the the eye. The visual rays are in a continuous bundle. The eye feels their direction and length.

Vision results from the interaction between visual radiation and colour, helped by external illumination. Colour is an inherent property of bodies, a layer on them. Through colour, other properties of bodies such as shape are perceived (Lindberg, 1976; Ronchi, 1970).

Combination:

Gorgias (480 B.C.):

Colour is the emanation from a body which is perceived (Ronchi, 1970).

Plato (427-347 B.C.):

A stream of light or visual fire issues from the observer's eye and coalesces with the brightness from the object. This creates a single homogeneous body stretching between the eye and the object, which serves as a material intermediary between the visible object and the eye. Colour is an effluence of bodies (Lindberg, 1976; Ronchi, 1970).

Medium:

Aristotle (350 B.C.):

Aristotle presented the first orderly theoretical discussion of vision. He strongly criticized Empedocles' and Plato's hypotheses of emission from the eye. He also disagreed with Leucippus that colours were emissions.

The object sends its visible qualities through the intervening medium to the eye. The medium, called the "transparent" is a nature or power in all bodies, but especially in transparent bodies such as water and air. It is not something we see but something through which we see. Light actualizes the transparent so that bodies become visible. The eye is mainly composed of water so as to take part in the transparent and be receptive of light and colour. Sight takes place when the water substance of the eye is moved by the visible object and takes on its qualities. The eye "becomes the object".

Colour overlays the surface of objects and has the power to move the transparent. Colours derive from mixtures of blackness and whiteness. Colour is whatever is visible; it is, however, only visible in light. It produces changes in the medium and this is transmitted to and acts on the eye. (Lindberg, 1976).

Galen (131-201 A.D.):

Galen's theory was similar to Aristotle's. But the emphasis was on the eye as the instrument of the medium, rather than on the object.

There is an external fluid which travels toward the eye and an internal fluid which, although not emitted by the eye, makes the eye more sensitive and likely to respond to the external fluid. The visual or optic pneuma alters the medium and makes it percipient.

Galen also did work on discovering the actual functions of various parts of the eye, such as the optic nerve, lens, and retina (Lindberg, 1976; Ronchi, 1970).

Chalcidius (early 4th C):

Sight occurs through a combination of inner light from the eyes, which is the principal cause, exterior light from a light source, and the light from visible bodies (Lindberg, 1976).

St. Augustine of Hippo (354-430):

The three factors in sight are the object, the act of vision, and the mind. The eye emits rays, similar to light. This light-like emission is weak and must be supplemented by exterior light (Lindberg, 1976).

EASTERN ISLAM:

Hunain (809-873):

Euclid and Ptolemy are incorrect. The theories of eidola and of Aristotle's "emanating forms" are also incorrect. If ten thousand people all looked at the same object simultaneously, then its form could not be conveyed to all of them.

Galen's theory is basically correct. The visual spirit of the eye meets the air and transforms it, and the air becomes the eye's instrument. The air must also be transformed by the sunlight. The visual power then perceives the form and colour of the object. Color produces a new change in the medium. The main organ of sight is the crystalline fluid of the eye (Lindberg, 1976; Ronchi, 1970).

Alkindi (813-873):

All intromission theories are incorrect. If intromission was correct, we should everything clearly and simultaneously. Intromission cannot account for the perception of shape, for example, we should see a circle turned sideways as a circle if its form is conveyed to us, rather than see it as a straight line as we normally do.

A form of the extramission theory of Euclid and Ptolemy is correct. Only extramission can explain the selectivity of sight and the clarity of vision being dependent on where the object is in relation to the observer's visual field, and also the temporal sequencing of vision Also, the eye is spherical and mobile; it has obviously been created to move and select the object to which it will send its rays. Weak-sighted people cannot see because their vision lacks the power to reach the object.

The visual rays issue in every direction from all points on the eye's surface, behaving the same way as external light rays. The rays are three-dimensional; Euclid's idea that the rays have length and no width is absurd. The cone of visual radiation emitted is continuous. If the eye and the air are each individually one substance then they must act as a whole. Also, for us to perceive objects as wholes, the cone must be continuous (Lindberg, 1976).

Alhazen (965-1038):

"Alhazen was undoubtedly the most significant figure in the history of optics between antiquity and the seventeenth century" (Lindberg, 1976, p. 58).

Extramission is incorrect. A person's eyes are affected or pained by bright light and by reflected bright light. Also, staring at a white object and then at a dark place reveals an after-image. These facts show that the eye is recipient of some external action. This "something" can be reflected by a mirror. Light, then, acts on the eye and the eye is affected by light. Since light acts on the eye and it is the nature of the eye to receive light, we must conclude that the eye only perceives the object by means of the light the object sends to the eye. Vision, then, occurs through the mixture of light and colour coming to the eye from the object's surface.

The Galenic idea of emission from the eyes is redundant. If light and colour are conveyed to the eye then the emission of rays from the eye is superfluous. The Euclidean visual rays are also an erroneous conception. If the rays from the eyes are corporeal, when we look at the stars the corporeal substance must fill the whole space between the observer and the stars without diminishing the eye. This is absurd. If the rays are not corporeal they will not perceive anything because perception is only in corporeal things. The overall conclusion to be drawn is that there are no visual rays, since they cannot explain anything, that is, serve no theoretical purpose.

As Galen showed, the eye is composed of parts such as the optic nerves, uvea and pupil. All parts of the eye are spherical on the surface and the centre of all ocular surfaces is a straight line through the centre of the pupil. The sensitive ocular organ is the lens ("glacial humour"). It receives forms which become weakly fixed in it, with their parts in the same order as in the objects they originate from.

Intromission is the correct theory but the versions of intromission put forth by the atomists and by Aristotle are both inadequate. (The atomists suggested that a collection of atoms issued from the object and conveyed its shape and color to the eye of the observer. Aristotle suggested that there is no corpuscular emanation but that coloured bodies, in the presence of light, change the transparent medium and that these changes are conveyed to the eye of the observer.)

Every point on the surface of a luminous or illuminated body radiates light and colour in all directions in straight lines. If there were no directional elements to the rays, the eye would see lights and colours as blurred and mixed. But this radiation does not result in total confusion for the observer because of refraction. As Ptolemy pointed out, light rays passing from a less dense to a more dense medium are refracted toward the denser medium. Rays perpendicular to the surface, however, pass straight through. Vision, then, is produced by perpendicular rays which are not refracted, that is, by rectilinear rays only. They constitute the unique set which furnishes the one-to-one correspondence between points in the visual field and in the eye. Also, the perpendicular rays are the strongest. They obscure any weaker impressions caused by the oblique rays.

Perception ends in the brain. The refracted forms are travel through the optic nerve to where the forms from each eye are united. This movement beyond the lens is partly optical and partly physical (Lindberg, 1976; Ronchi, 1970).

Avicenna (980-1037):

The Euclidean extramission theory is incorrect. The idea that the eye can send out enough substance to encompass a very large body or to reach a body as far away as a star is absurd. Also, if extramission is true, distant objects should appear as their actual size and shape. If visual rays exist, they must be able to penetrate water since we can see objects below water, but in doing so they should show some visible trace of themselves, which they don't. The idea that the eye transforms an intervening medium is also wrong, because if this was so, it would be transformed for all observers and weak-sighted people could see as well as strong-sighted

Vision occurs because a transparent medium transports the form of the thing to be seen to the eye. When light falls on the visible object, it projects the image of the object onto the eye. This mirror image is taken by the crystalline humour to the hollow (optic) nerve which is the centre of vision (Lindberg, 1976, 1983).

Averroe (1126-1198):

Avicenna is incorrect. The extramission theory is incorrect because it implies the ability to see in the dark. The atomists are incorrect because the forms of the bodies would be too large to be conveyed to the eye in their actual size. Also, we can see different bodies at the same time and for this to take place, the forms would have to cross over and contact each other

Aristotle is basically correct. Air receives the forms of objects and brings them to the eye (Lindberg, 1976, 1983).

WESTERN MEDIEVAL SCHOLASTICS:

William of Conches (1080-c. 1154):

Vision requires an interior ray, exterior light, and an opaque object. The interior ray originates in the liver and eventually reaches the eye via the brain. The interior ray mixes with the external light and reaches to the object. It diffuses over it and assumes its shape and colour. The ray then returns to the soul via the eyes. All this takes place instantaneously (Lindberg, 1976).

Adelard of Bath (c. 1090-c. 1150):

The brain generates a corporeal fiery air which passes out through the pupil to the object. The fiery air is impressed with the form of the object, then returns instantaneously through the eye to the soul (Lindberg, 1976).

Robert Grosseteste (c. 1175-1253):

Natural agents send out their power, called "species", to surrounding bodies. The effects of the species resemble the agent. For example, bright bodies emit species which produce brightness in the eye of the observer. Since species issue from all bodies, they must also issue from the eye and play a role in seeing. The radiation from the eyes, when combined with exterior radiation, completes vision (Lindberg, 1976, 1983).

Albertus Magnus (1206-1280):

Opposed the extramission theories of Plato, Euclid, Empedocles, and Al-Kindi, and supported Aristotle (Lindberg, 1976).

Roger Bacon (1214-1294); John Pecham; Witelo:

Sight is basically a matter of intromission. "But aside from citations and format, the theories of vision expressed by Bacon, Pecham, and Witelo are essentially the same as Alhazen's." (Lindberg, 1983, p. 331). "Roger Bacon and John Pecham adopted Grosseteste's doctrine of the multiplication of species and incorporated it in their theories of vision drawn from Alhazen" (Lindberg, 1983, p. 336-337).

THE LATER MIDDLE AGES (14TH AND 15TH C.):

The Perspectivists:

The intromission theory was basically accepted. Attempts were made to apply geometry to optics, especially as regards refraction. The psychology of perception was investigated (Lindberg, 1976; Ronchi, 1970).

Aristotelian Commentators:

Aristotle's basic ideas were supported, with the addition of some elements borrowed from the perspectivists (Lindberg, 1976).

The Theological Tradition:

The act of seeing involves intuitive cognition of the object by action at a distance. There is no transmission of forms of any kind (Lindberg, 1976).

WESTERN EMPIRICAL SCIENCE, c. 1600:

Johannes Kepler (1571-1630):

"Kepler's successful solution of the problem of vision early in the seventeenth century was a theoretical triumph" (Lindberg, 1976, p. x).

The weak point of the perspectivist theory of vision is their attempt to consider only perpendicular rays as contributing to the image, and to dispense with oblique rays. This idea is discredited both by the anatomy of the eye and by mathematical and physical considerations. The crystalline humour (lens), then, cannot be the place where the image falls. The luminous rays must be reorganized by the eye, recreating an image which falls elsewhere. This new site of the image is the retina, which receives the image refocussed by the lens. The retinal image is a real optical image, upside down and reversed from left to right. The explanation of how this image is then perceived right side up and unreversed is not a matter for optics because it is a non-optical phenomenon (Lindberg, 1976).

Francesco Grimaldi (1618-1663):

"In all the philosophy of the previous centuries (before Grimaldi) the interpretation of colour presented serious difficulties. Many strange and discordant ideas had been put forward, but all seemed to agree on one point: that light was something quite distinct from colour....Colour was a quality of the object" (Ronchi, p. 141).

Light is a material phenomenon. Experiments show that light can be be coloured by reflection, by refraction, and by diffraction. Diffraction occurs when a beam of light, made very narrow by projecting it through a small hole, casts on a screen a shadow larger than that predicted by geometry. This shadow also has luminous coloured bands around its edges. If light can be coloured by any of these means then the change must occur in the light itself, since this is the only commonality in the experiments. Observation of coloured beams leads to the hypothesis that this change in light is due to an "undulation slightly varying", by which the light acts on the eye. The great variety of colours is due to the great variety of undulations. Some colours are simple and others are combinations of simple colours. The simple colours are red, yellow, and blue. It can no longer be asserted that colour exists within bodies and is distinct from light (Ronchi, 1970).

Marcus Marci (pub. 1648):

Experiments carried out with triangular prisms show a correspondence between colour and refraction. It is impossible to have the same colour with a different refraction or different colours with the same refraction. The rays which carry the same colour are parallel. Colour is independent of the intensity of the beam (Ronchi, 1970).

Isaac Newton (1642-1727):

"In 1666, Isaac Newton laid the foundations of colour theory in a series of fundamental experiments which he described in his *Opticks*, not published until 1704" (Wasserman, p. 8).

Light is not homogeneous but consists of different kinds of rays, varying in refractibility. This refractibility is directly related to their colour. Colours, then, are inherent to light. Simple, homogeneous (monochromatic) rays cannot be refracted. Different coloured rays can be mixed to produce another intermediate colour, which, again, can be separated by refraction. The simple or primary colours are red, orange, yellow, green, blue, indigo, and violet-purple, and an indefinite number of intermediate gradations. The primary colours may also be produced by composition.

White light is a mixture of the primary colours in the proper proportions. Whiteness is the "usual" colour of light. The prism produces colours by refracting the rays of different colour. These various rays diverge to different parts of the retina.

Bodies appear coloured due to their tendency to to reflect one kind of light more than another. The other rays are "stopped" and "stifled". Bodies can be made to appear any colour by illuminating them in a dark room with uncompounded (monochromatic) light of different colours. They always appear, not their own colour, but the colour of the light illuminating them, although they are most bright and vivid when illuminated by light of their own colour. In daylight, the objects appear their "normal" colours because they mainly reflect those colours.

If objects are illuminated, not by homogeneous light but by ordinary prismatic colours, they will tend to appear of a colour intermediate between the light cast on them and their own daylight colour (Newton, 1931; MacAdam, 1973).

George Palmer (Publ. 1777):

Every ray of light is made up of three other rays only, yellow, red, and blue. Colored objects absorb the rays analogous to the colours which they seem painted and are perceived by the reflection of others. A white surface reflects all rays. A surface painted with the correct proportions of the three principle (primary) colorants will appear black. Any principle can become black by absorbing the rays not analogous to it when "its density exceeds the proportion of its own ray" (MacAdam, p. 40).

The surface of the retina contains three different kinds of particles analogous to the three principles and sensitive to its own ray. The sensation of white is produced by the complete motion of these particles, while the sensation of black is produced by their static state. Sensations of colours are produced by differing motions of these particles (MacAdam, 1970).

Thomas Young (1773-1829):

Each sensitive point of the retina contains three kinds of particles corresponding to the three principal colours, red, yellow, and blue. Each particle is put in motion by undulations (waves of light) varying from "perfect unison".

"Perfect" sensations of red are produced by a mixture of red and green light, while "perfect" sensations" of blue are produced by a mixture of green and violet light.

The three "simple sensations" combined produce the seven "primitive distinctions of colour", but there are an infinite number of possibilities beyond those. The three simple sensations are red, green and violet. Yellow consists of red and green, crimson of red and violet, and blue of green and violet. However, this blue is not the blue of the spectrum. White is produced by combining all three simple sensations (MacAdam, 1970).

APPENDIX D
TRANSCRIPTS OF RESEARCHER INTERVENTIONS

THEORIES OF SEEING

After you did your preevaluations for me, I looked through them and I tried to see what sort of ideas you came up with. The sort of ideas you came up with basically divided into four, what you could call scientific theories. In other words, you people have your own scientific theories about how we see. I need to draw some ray lines in here in a moment, but at the moment I've just put them up here on the blackboard like this. Great art work, eh? For purposes of being able to talk about them, I've called this one the "illumination theory", this one the "visual rays theory", this one the "two-way theory", and this one the "reflection theory". That's so we can talk about them.

What we're going to do is this. We're going to take these four theories. Mr. Newton and I have divided you up into some discussion groups that are going to work together on these. In your group you're going to sit down, take a look at these theories, and discuss and debate them as to which is the best way of describing the way in which we see. When we talk about discussing and debating ideas. we have to think carefully about how the groups can work. Let's say we're sitting here having a lesson and I'm your teacher. I ask Mark a question about how we see and Mark comes up with some ideas and I say, "Mark that's the dumbest thing I ever heard. How could you ever come up with an idea like that?" How much participation are we going to get out of Mark for the rest of the class and maybe the rest of the year?

Voice: None.

Exactly. He's going to say, "He's not interested in what I think and so why should I tell him?". So what you have to do in your groups is you have to try to operate in a way that you encourage people to present their ideas. In other words, this manner in which we treat people's ideas has to extend to you as well as to me. So guidelines for the way the groups might work are these: We should consider everybody's ideas in the group. In other words, everybody should have a chance to present their ideas. We should take them seriously. So you're not thinking, like I just said, "Well this is the dumbest thing I ever heard", you're thinking, "Well maybe there's something in what this person is saying so I'm going to listen and try and hear what they have to ay". Because all these ideas that you people came up with, somewhere in the history of science represent the way that scientists once thought or think now today. So in other words, famous scientists in the past have had exactly these same ideas, so how we can say these are dumb ideas? We can't. The other thing is, in your group you don't have to reach agreement. Not everybody has to agree on the same ideas. You could have two people in your group that hold this theory and maybe three hold this theory and maybe one holds this theory. That's fine. You don't have to reach agreement.

So on the one hand you have your own ideas and you should be able to stick up for your own ideas. And on the other hand it's all right to change your ideas. So there's a sort of a balance there. But you should change your ideas because you've thought about what you're thinking and you've come to a conclusion that maybe it's not the best way of thinking about these things. You shouldn't change your ideas because Joe Blow whose your best friend disagrees with you or because you want to impress the person beside you. In other words we have to have some, what we call "intellectual honesty". You have to stick up for your own ideas as much as possible.

What we're going to do with these is after you've gone through them in a discussion and you've figured out what might be the best way to describe how we see objects, we're going to go on a little from there and have you think of ways in which you could, I guess you could call it, prove or verify or show that your idea is the best one. Now in science there's two ways we do that. This is a very simple explanation. One is what we call logically, and all that means is that what you're saying makes sense. If it's a beautiful hot sunny day out and I put on my overcoat and my hip waders and go outside, you can say that what I'm doing is not very logical. Because I don't need to put on my overcoat and my hip waders if it's a nice day out. That's not being logical. But if it's a nice day and you wear a T-shirt and pair of shorts, that's logical. So by logical we just mean that what you're saying makes sense. It fits together. What is the other way in which science that we try to prove something is correct? And this in a sense is what distinguishes science from other ways of thinking. Yes, Maurice?

Maurice: Experiments?

Exactly. So what we're going to try to see is, is there a way in which you can logically, sensibly support your idea. Second, is there a way in which you can think of an experiment you could do which would also verify or show that your way of thinking is the best way of thinking about what we're trying to decide? You may not be able to think of an experiment but you may be able to think of a logical way of describing what you're doing. On the other hand, you may be able to think of an experiment but you may not be able to think of a logical way of explaining your argument. That's okay. One or the other, both, whatever you come up with.

So without further ado, I'm going to draw in the ray lines up here and it will help to explain what people think in these theories. The essence of this illumination theory is that light from the sun lights up this tree and we see it. That's the basics behind this theory. The essence of this theory, what I call the "visual rays theory", is that the sun lights up this tree and we have sort of a line of sight from our eyes to the tree. "Visual" is a word referring to your eye. The "two-way theory", which some of you came up with, is that the sun lights up this tree, some of the light goes to us, and also our eyes see the tree like that. That's why I call it the "two-way", because you show light coming off the tree to the person and you also show a line of sight going to the tree. This last theory is what I call the "reflection theory". This "reflection theory" says that light goes to the tree and then reflects off to our eyes and that's how we see the tree.

So these are the four theories that you people came up with. And as I said before, in the history of science, people, scientists have thought one or the other of these theories to be correct. So there's nothing dumb about them. These have been thought of in the past.

Here's what I would like you to do in your group. Sit around together, have everybody present their ideas on one of these theories and why they think that it's correct. Have a little discussion debate in your group. The important thing is that your group should function all right, that the debate should go on about the topic, that it should focus on the topic, and that everybody should talk about it. If your group isn't functioning too well, try and stop and get it going again together, or maybe ask for some help from Mr. Newton or myself.

The basic idea is to get into the groups in a minimally disruptive way: pick desks close, pick a corner, go into it, sit down, and start on the topic. I am going to take this recorder and move it to the group of the people I interviewed, not because I like them better than everybody else but I have to make a focus somewhere and I picked that group as being typical of everybody. I'm also going to try to come around and listen to what other people are saying and I think Mr. Newton is going to be interested in what people are saying too. So, as I write the people in your group on the board you can start assembling yourselves.

Mr. Newton: Do you want them to write down their ideas or is it basically conversation right now?

Basically conversation right now and then at the end we'll try and sum up.

Now these groups are purely at random. I don't know any of you. I put you into these groups and Mr. Newton adjusted them a bit.

Now if you're not sure how to start off, one of the ways you could start is I noticed you have a PMI (note: from Edward de Bono's CORT program) chart over there. One of the ways you might start is by taking each one of these theories and having everybody in the group address what they think are its good points and its bad points. That's another possible way of starting off. Instead of everybody in the group saying what they think is the best theory, you might start from each of the theories and have everybody in the group say what they think about them. What I'd like you to be able to do at the end of the discussion is when we all get back together again I'd like everybody to have a fairly good idea of which one of these theories they think is the most appropriate way, and hopefully, some ways in which they could prove that their ideas are better than any of the other ideas. So how about moving into groups and we'll start this off and see how it goes.

EVIDENCE FOR THEORIES OF SEEING

I'm going to be really brief here. I just want to say a couple of things. The purpose of what we're doing here is for you to try to verify your theory or, as Allison said, try to disprove another theory or theories. And this can be done using materials experimentally, or what we call the thought experiment, like the example someone brought up about what happens in their bathroom. That's something you can't do in here because you can't bring your bathroom to the classroom. It's very difficult. Now, as Mr. Newton said you could use this apparatus or you could not use it, or you could use part of it, whatever. You're going to work in your groups and the way we're going to do this is this. In your group each person in turn will present their experiment to their group. Because we wouldn't have time for everyone to do presentations for the whole class. Then, after they've presented it you can have a discussion about whether you agree or disagree with what they say about their experiment. They may say, "My experiment proves X", and you may say, "It doesn't really because....". So what I'm going to do is we'll have about seven minutes a person, a couple of minutes for presentation and about five minutes discussion and then I'll give you a signal, I guess the light signal, and that'll be a signal for the next person in the group to do their presentation and to have a discussion and debate on that. And try to remember that your groups function best when everyone has a chance to speak, when somebody's speaking you don't interrupt but you let them finish, that you take other people's ideas seriously, and that you allow people to disagree. You don't have to reach agreement in your group. So, that's it. Any questions?

REFLECTION THEORY OF SEEING

What I would like to do today is I am going to present to you one of the theories we've come up with about how we see. And I'm going to attempt to show you how this theory seems to best describe the way we see. While I do this the most important thing is your attitude toward what I'm doing. The most important thing is that you try to understand what I'm doing or what I'm saying and how it connects to what we're trying to learn.

As we all know, sometimes in school, or maybe a lot of times in school, we often prepare for a test by simply memorizing what we're supposed to know for the test. And then we go and we write the test and we get a really good mark on the test and then a week later we forget everything we memorized. I guess that's part of the nature of our school system. But the reason we forget it is we didn't really learn it in the sense that we didn't really think it through. Or some people say we didn't make it our own, we didn't make it our own learning. To understand something requires you thinking and participating at the same time, thinking about what you're involved in. So what I'm going to ask you to do is to participate with me in what I'm doing, not by trying to memorize the ideas I'm giving or presenting, not by saying to yourself, "Now I know the answer, oh that's the correct theory, okay fine", and then there's no more to know. No we don't want that. I want you to look critically at what I'm saying and doing. I want your attitude to be I'm not really going to accept what he's saying unless I really understand it and unless it answers all my questions about seeing. And a lot of you did have a lot of questions, very good questions, and I want you to keep those in mind and I want you to ask them again today. And don't be satisfied unless your questions are answered.

So the most important thing today is not that you end up agreeing with me, although you may, but that you think about what I'm saying and doing. See, while I've been doing this research myself to do this work with you, I've learned quite a lot of things about light that I didn't understand myself and the reason I did was because I had to learn it to do it with you. So what I'm trying to do with you is I'm trying to take you through that same process with me so that you can think about those questions too. So the most important thing is not that you agree with me but that you think about what I'm saying and I'm doing just like I had to do when I was doing the research. So it's that thinking process which is going to lead you to a better understanding of science, not memorizing some ideas.

Just before we start and I'm just going to mention three facts about light upon which we should all agree, well-proven facts. And they are, one--these are important to keep in mind--light travels very fast. As you all know when we turn out the light the room is instantly dark. You don't turn out the light and wait around for awhile till the room gets dark. So light travels very first. That's important to know. The second one is, that light travels in straight lines. We'll just ignore Einstein's Theory of Relativity for the moment. Light travels in straight lines which means when we put something in between a light source and you there's a shadow. That object blocks those straight lines of light which creates a shadow. The third thing is....Now this last one you may not be quite sure about this one but we'll just keep it in mind because I think it is important. We certainly must agree that light reflects when it hits some things, so I'm going to propose that light reflects when it hits anything. In other words, it bounces around.

From these now, I'm going to present some evidence about this. The first bit of evidence I'm going to present is that we can't see in the dark. So I'm going to say that from that we have to assume that light is absolutely essential for seeing. In other words, seeing has something to do with light because we can't see in the dark. And by seeing in the dark I mean like if it's pitch dark, it's totally totally dark, we can't see. I think we'd all have to agree with that.

Now the second thing I'm going to bring up is something that Allison mentioned and that is when you're outside in the winter and you're skiing, say, and the sun is shining really brightly your eyes get dazzled. You look at the snow and your eyes, you get this real glare in your eyes. And what I'm going to propose is the reason you get that is because light reflects off that snow. And I'm going to say that that's proof that light reflects off things and that we can extend that to other things. So, what theory am I trying to present here? What I'm trying to say is that the idea of reflection is correct, that this is the way we see. Here's our tree, here's our light, and here's our person. This is how we see. That's what I'm trying to present. Again, I don't want you to necessarily agree with me, I want you to listen to what I'm saying and think about it.

A little more evidence here. This is the human eye. Now, the reason the structure of the eye is important is I'm going to propose to you that only the reflection theory is correct because the way your eye is made it is not made to send anything out like some sort of ray that makes you see or some sort of sight, it's only made to receive. That the light comes in through the lens of your eye, goes on the back on your eye, which some of you may know is called the retina, and that this is how we see, that that creates a picture that we see. So I'm going to propose that against the idea that there's some line of sight from here to here, is, that there is nothing in the human eye which you can show me that is a mechanism for sending anything out from your eye, that your eye is only trained to receive. Things only come into it, they don't go out.

Now, and a little more evidence that the eye is built to receive light, I'm going to show you a picture here of an animal that hunts at night. This is a tarsier. And I think one of the first things you'll notice about this is that his eyes are very large. And I would put to you that the reason his eyes are very large is because there is so little light at night for him to see, reflected light, that his eyes have to be very large in order to get enough light to see. So I'm putting this forward as some more evidence for this idea of reflection.

And the last thing I'm going to say, and I'm just going to stop here, is this. Do you see this chalk, Barbara? When you see this chalk do you see this chalk as how big it really is or do you see it smaller than it really is from where you're sitting? Smaller? When we see objects from far away they always look smaller, would you agree? Okay, well I am saying that that can only be explained by the fact that we don't see objects what we see is images of them, like pictures of them in our eyes, and that if we did see the real objects they would look exactly the size they're supposed to be. So I'm presenting that as my last bit of evidence. That what you see is a sort of picture I guess you could say, in your eye of this tree. You don't really see the tree. And I'm saying that how this image gets from here to here is by light. Not that light carries the image but light is the image. So that's how I'm establishing a connection between what you see and you, that light is the connector and that that's how it gets from the object to your eye.

So that's my proposal. So what I would like to hear from you is the questions you would have because I'm sure not everybody would agree with this. Which is good. So what I want to hear is what difficulties you see with this possibility and what objections you have to it and what it doesn't explain for you. And this I think is the most important part of we're doing.

THEORIES OF COLOUR

I'm going to start off by answering two questions that were asked me the last time I was here. Actually four questions were asked me but two of them have to do with colour. One's a question that Donald asked a long time ago and I've still got it in my head. But I'm not going to answer that yet because it has to do with colour. But I had two questions yesterday about how we see that I'm going to answer. The first one was Allison's. She said, "If we see images of objects, how do we see objects when they move?" Basically the explanation is that your eye continually focuses as the object moves you it's like you take a new reading every time the object moves. It's like there's a series of images coming to your eye, one after the other, and it gives you the picture of movement. And Susan asked me why if a cat's eye is the same size as ours, why can cats see in the dark better than we can. If you've ever looked closely at a cat's eye you notice in the pupil they have kind of a slit like that? Well, it's this slit which allows the pupil of the cat--which is the part of the eye that catches the light,--to open up further than ours. So the cat's eye has more capacity to expand. The pupil part can get bigger than our pupil. So that's why it can see better in the dark. Yes?

Voice: I've just heard they felt around with their whiskers.

Yes and they also use their whiskers to feel their way around. Okay so I've still got two questions in my mind. One was, how do we know that certain animals can't see colour, and Donald's question is if an object neither reflects nor absorbs light, what would it look like. But I'm not going to answer that question right now.

Okay, this is very simple and straight forward. I have two books here. This one is red. This one is blue. The question we're trying to answer is, "Why do we see this as red, and why do we see this as blue?" In other words, why do objects appear coloured. Now you people came up with two possibilities. So we got a little simpler this time. Last time we came up with four possibilities. This time we've only got two.

This is the first. (Writes on board: "Colour is an innate property of objects.") Now when I wrote it's an innate property of objects all I mean is that colour has only to do with the object and nothing else. In other words, no matter under what situations or circumstances we have this book we will see it as blue. So it has only to do with the book, only to do with the object. The other theory--so I think we can call this the object theory, object meaning what we see--the other theory that you came up with is (Writes on board: "Colour is a result of the way objects interact with light".) We call this the light theory. What this means is that in order to see colour it has a lot to do with light and it's not just the object that's (inaudible) here. So there are two things involved here, light and objects, and, of course, your eye because your eye has to see it.

Now, when we have a theory we find that scientific theory is not just one idea it's a bunch of connected ideas. Let me give you an example. I know this has never happened to you but let's say your teacher says to you, "Why didn't you get your math homework done?" I know this has never happened to you. So you have this theory and you say, "The reason I didn't get my math homework done is because I didn't have enough time." So that's your theory of why you didn't get your math homework. However, your teacher is not willing to accept that, and says, "Well what did you do last night with your time?" So you say, "Well, let's see from four to five-thirty I had to go the store and from five-thirty to six-thirty I had to eat supper, and then from six-thirty to ten-thirty we went to my aunt's place and then I had to go straight to bed." So then your teacher says, "That sounds pretty good to me but I've noticed for the last month you haven't done your math homework." So now you have to think of something else that connects with it and so on and so on. So you start off with a theory about why you haven't done your math homework, but there are other things that are attached to it, that you have to explain to.

There are three other ideas that are attached to both of these. I'm going to put them in here because we can't really go into these unless we look at these other three attachments. This has to do with this: (Writes on board: White light is pure and colourless.) Now by "white light" I mean light from lights, the usual light. light from sunlight. (Writes on board: White light "brightens up" objects. We see colour because we "look at" objects.)

Now I think you'll notice the other things that we have to add to this theory go back to what we talked about before, how we see objects. So this is an illustration of how ideas are all connected. If we say that colour is only in objects then we have to say that there's no colour in this light, that it's just white and that's it. We also have to go on with what we said before, that the function of this light is just to brighten up objects and then that we see because we look at something. And the opposite of that would be this. (Writes on board: White light is a combination of all colours. Objects absorb certain colours of light and reflect others. Special cells in our eyes are sensitive to certain reflected colours.)

I have another reason why I'm doing this and I'm going to explain it to you in a moment. If colour has to do with the way objects and light get together, then colour has to have something to do with light also. And as you can see what follows from that is a sort of variation of the reflection theory we were talking about. White light is a combination of all colours. Objects absorb--that means they take in, it disappears--certain colours out of white light and other colours reflect off the object, and those are the ones that the special cells in our eyes see. Now, why does this is helpful is, when eventually you try to prove your theory, you may not be able to prove this or this but you may be able to prove one of those other three. Which one of these, for example, looks like you could probably prove one way or the other. Do you see either one of those three statements that might be possible to prove by an experiment? What might be provable by an experiment? Richard?

Richard: Special cells in our eyes are sensitive to reflected colours.

Researcher: Okay, how could we do that?

Richard: Well we take colours and put them on say those light boxes we had and we take different colours of sort of transparencies and put them over the light and then we project it up to our eyes and see if we're sensitive to those kind of colours.

Researcher: But I think we'd require dissecting our eyes to find those cells. I think we'd have a problem there because I don't think we're allowed to cut each others' eyes into little pieces. What else might be provable or checkable by an experiment. What do you think, Hugh?

Hugh: White light brightens up objects.

Researcher: What can we do with that?

Hugh: You just take a light and shine it on the object.

Researcher: But if you remember, the problem we had when we were trying to prove how we see was it was very difficult to devise to do that, and this was one of the parts of that theory. Now we had a great deal of trouble with that because we couldn't think of an actual experimental way we could prove that. Monty?

Monty: White light is a combination of all colours.

Researcher: or, what's the opposite of that in the other theory?

Monty: Black light is a combination of all colours?

Researcher: Well, this is white light is a combination of all colours. This is white light is pure and colourless. Now do you see that that's a possible way of getting a handle on which of these theories is correct. Because if light has nothing to do with colour, then it's just going to be something that shines and that's it. If light does have something to do with colour then those colours must be in that light somewhere and you guys must be able to possibly find them. Yes Maurice?

Maurice: We might be able to disprove the object theory by getting a transparency, having pieces of white paper, then you take the transparency putting it over the light, and shining it on the paper.

Researcher: Okay, now the reason I raised this is because as I said before last time you had trouble thinking of actual ways to do this. So what I'm trying to do here is I'm trying to give you some hints or clues as to some ways in which you might go about proving which of these theories is correct. Donald?

Donald: For white light is a combination of all colours you could take one of those rocks when you shine the light it has red, blue and yellow on the other side, and then that would prove colour and then that would also prove white light is pure colour.

Researcher: Those are called "prisms", right?

Donald: Yeah.

Researcher: Okay, Monty?

Monty: Well you get proof of white light is a combinations of all colours by getting different colours of transparencies, sticking them together and shining a light through them.

Researcher: Combining different colours of transparencies. Ah. Okay. So what I'm going to suggest you do is you know what groups you're in and I want you to split up in them and I want you to talk about this for about ten minutes and I want you to do the two things we did before: decide which of these theories is the best one, and second of all, decide an experimental way in which you can prove it. And what I hope I've done today is given you a little more information on how you might do some experiments to prove this. Because last time we had a lot of difficulty with that. So what I would like is I would like the group that I interviewed to be over here again so I can record them. And I'd like the rest of you to go into another part of the room with your group and spend about ten minutes having a discussion and debate about which of these is better. Go.

EVIDENCE FOR THEORIES OF COLOUR:

First of all, what we're going to try to do today is to investigate the second of our two main questions. Which is? Monty?

Monty: How do we see colours?

Researcher: Not quite. Yes?

Voice: Why do objects appear coloured when we look at them?

Researcher: Right now we're going to do that in two ways. The first one, Donald, you suggested how we could go about this using the prisms. What was your suggestion?

Donald: Well if we took a flashlight and shine it into the prism we could see, I think it's blue, red, and yellow through the other side.

Researcher: Okay, so that's the first idea, is to shine the white light which is the flashlight on the prism and see what happens. Our possible explanation for what happens when you shine the flashlight on the prism and as you all know it's like for example, a rainbow, is that the white light breaks up into many different colours. But I would put it to you that there may be some other possible explanations and as you're doing it in your group think of what some other possible explanations might be. Now the second thing we were going to do was to look at some coloured objects in different coloured lights.

What we have up here is some of these transparencies and these work really well because they will cut out pretty well all the white light and you'll only get red light, and as you can see on the box they fit right onto those squares on the box. So there's different colours of these and before we start I'm going to have you come up in groups and collect one of each colour. The next thing we have is these ones here which mask completely one of your rectangles so there's no light at all coming out of it. So if you just want to work from one rectangle, you can block all the other ones with these black ones. These ones and these ones have all three colours on them. So you could play around with that. You can put that on and try your coloured object in different colours of light and see what you see. By the way, when you see something try to make sure it's what you see and not what you expect to see. And, for looking, what I collected was a whole pile of little coloured squares and there are six different colours of squares. So you can try different combinations, for example, look at the blue one in red light, look at the yellow one in green light, and so on. So you have several options there that you can do.

Now, why are we doing these things? Because we want to see if we can sort out this question of why things look coloured when we look at them. One of the problems with scientific theories is that they're thought up to be under perfect conditions. in the normal world we don't go around looking at things in red light all the time. We go looking at things in what we call white light. So the ideas that we have about how we see colour come from just living in the ordinary world. In science, what we try to do is we try to create perfect worlds, a world where all the light is perfectly red, a world where all the light is perfectly blue. So since you don't have experiences with those worlds, it comes as a whole different kind of experience to actually live in that world for a brief period of time. So that's what you're going to try to do. You're going to try to live in a different world for a little period of time, a world where light is coloured rather than white.

What I'm going to ask you to do is split up into your groups when I ask you, and then I'm going to have one person from each group come up and get enough materials for each group, and then you can go back and go to work. Now, at each station there's a flashlight. You can turn it off and on as you need it in order to see what you're doing. Because it's going to be dark in here. We're working here in the dark and we're working here with electrical equipment. Therefore it would be really silly if we started fooling around because someone will get hurt. Also, we'll have to cancel all the activities and that'll be it. It's going to be very dark in here but you should have enough light to operate.

REFLECTION THEORY OF COLOUR

I would ask you to try to pay close attention here because I think this is difficult to understand. I have difficulty understanding it myself. So the question that arose after yesterday's work in the gym was, "Why do objects appear coloured?" And the reason the question came up again was we noticed that a red object when viewed in green light looked black. And this didn't seem to make any sense with the way we think about colour now.

So the first thing I think we have to look at if we want to understand this is the nature of white light. Now by white light I mean normal light that you get out of lightbulbs and you get from the sun, the ordinary light we see by. That's what we call white light. Now, what I'm going to put to you is white light is not something that's pure and colourless but it's actually a mixture of all the colours. And when you put them all together they make white. And I'm going to present a little evidence for this. And the first evidence I present here--will you get the lights please Nora, it'll just be a little easier to see--is one of these little guys, these prisms. And I think you're all familiar with the way a prism works. As you can when we put the prism here up in front of the beam of white light that comes out of the overhead we suddenly notice that we don't see white light but we start to see colours. And I think you can all see them there.

Now we have to have an explanation for where these colours come from. And I think we'd have to agree that if the only thing between here and this screen is this prism, somehow the colours are coming out of this light and this prism is doing something to this light. So what I put to you is that what this prism is doing is it's breaking up this white light coming out of here into its colours. And it's showing some evidence for what I'm saying.

Now the second piece of evidence I would present for this is that in nature after it rains we see rainbows. Why do we see rainbows? Where does the rainbow come from? Laurie?

Laurie: (Inaudible) the rain.

Researcher: Okay, so the rain is involved. Right.

Laurie: The light.

Researcher: Which comes from?

Laurie: Sun.

Researcher: Okay so we have rain and then we have sunlight. Then.

Laurie: And then the raindrops is like that prism.

Researcher: Good. Okay. So the raindrop is like a prism and it takes the light from the sun and breaks it up into colours. Okay. Yes?

Richard: If the rain was heading west and you passed the city and you went east and you looked back on the city and it was still raining here then you'd see a rainbow.

Researcher: So what we're saying then is these raindrops act like prisms. So now what I've tried to present here is some evidence that we can break white light down into colours. Now I demonstrated this to you yesterday. And I showed you with these different coloured filters here what happens (see footnote, p. 154). Obviously this is turning that red because there's red filter. So that is doing something. This one is creating a blue colour there. This one is creating a yellow colour there. Now, then what I did yesterday in the gym was I took these three filters, put them together, held them in front of the flashlight. And we won't get such an effect here because isn't as concentrated. But as you can see somehow we've lost all our colour. We're still shining through these filters. I'm holding them in front here, but we don't have colour. So I submit to you that the only conclusion we can draw from that is that when we can put these colours together again we can get white light. So I'm showing you this from two points of view, that we can break white light down into colours and that we can take colours and make white light. So I'm presenting evidence from both sides of the picture. Yes Maurice.

Maurice: I thought I saw a clear transparency there.

Researcher: Yeah, this is just a clear one. I'm just trying to keep these protected. They actually belong to my wife, they're part of her photography kit and I was told to be very careful with them. Ian?

Ian: When we had the boxes, you know down on the stage? When I put all the colours they didn't do that. Is it because it was too dark, the filter?

Researcher: It has to be the right mixture. Like I said before, the thing about scientific theories which makes them difficult to understand is that they sort of only work in a perfect world. So a perfect world would be you would have to have exactly the right shades of these colours for it to work. And you would have to play around a bit before you could get that. Yes Donald?

Donald: Could you take the colour out of (inaudible)

Researcher: Well I think that maybe that goes back to the previous question you asked about things would be transparent if they didn't have anything in them.

If we agree that white light has these colours in it, I think we take a long step toward understanding why we see colour. And it simply looks like this. Okay let's have a light source here. Our famous flashlight. Okay, Now here's our white light. And it's got in it all colours. Now here is our green filter. And after the green filter, we don't have white light anymore we have green light. And this green light shines here on this red object. And our eye, which is looking at this, sees black. This is our mystery that we're trying to solve. Okay, I'll present to you a possible explanation. The white light comes out of the flashlight and it hits this green filter. What this green filter does is it absorbs, it takes in, it uses, it grabs hold of all the colours except green, and it won't let anybody through except green. So it takes all the colours out of the white light and stops them, and green is the only one that travels through. The green light shines on this red object. Now for me to see this object as red, there has to be red light reflecting off it. But I don't have any red light left because it got stopped back here by the green filter. So the only light left is green. And this object is not green, it's red so it absorbs that green light and all we see is black. Now this is a little confusing but let me explain how we ordinarily see it and I think you'll understand. So let's say we don't have this green filter in here. Let's come this way so we can get our guys together. We don't have this green filter here. We have white light, here's your eyeball, and you're seeing red. What happens here is this white light comes along and it gets to this red object and this red object steals every colour out of this white light except red, and absorbs it, takes it in. You don't see it any more. So the colours that are in this white light except for red they get lost in here, they disappear in here. And what happens to the red? It reflects off and you see red.

That's my explanation. So ask me some questions. So we have two words: "absorb" means the colours go in, they disappear. "Reflect" means they bounce off. So you can see them. Yes Donald?

Donald: How do colours get reflected (inaudible)?

Researcher: What they call the stuff that's in these that causes it, is they call it pigments. There's a red pigment, there's a pigment in here that reflects red light. Now when we take a paintbrush and we paint this thing red, the reason we see it as red as we're painting is that this stuff you're putting on immediately starts reflecting the red light. But if you were painting this thing in green light, you would look like you were painting it black. Yes, Eleanor?

Eleanor: If you have a (inaudible) with different colours of paint and you mix together but they're not all mixed together, and you can still see different colours, how do you see the different colours?

Researcher: Because each of those colours would do its job separately. Each of those colours would do its job of reflecting separately. Maybe somebody could invent striped paint. You could go to the store and buy a can of striped paint. So you can see that it's really important....If we don't understand that white light is made up of all colours there's no way we can understand because it makes no sense whatsoever because then we don't know where the colours come from. Do you have a question?

Voice: I've noticed that also certain kinds of oil running along the sidewalk you can see a little rainbow in it.

Researcher: Right, yes. So how do we this? In our eyes there are special cells called "cones". And there's a cone for each of these colours: red, blue, and green. And what our eyes see, they are activated by being hit by these colours, so we see all the colours as combinations of these different colours by these special cells in our eyes. That's where your eye comes in. Now I'm going to do something a little different here today. I want you to try reading this because I really get the impression that I'm missing some people up here, that some people were getting a little wandering here. So I want you to try to read this through and this'll be like me talking individually to all of you. And then I would like to find out what it is you understand and don't understand, what makes sense to you and what doesn't make sense.

APPENDIX E

WHY OBJECTS APPEAR COLOURED

1. White light, that is, light from the sun or from room lights is NOT pure or colourless. White light is actually made up of all colours.

Evidence

A prism breaks light up into its colours.

Water droplets in the air after rain break up sunlight to make rainbows.

When we shine white light through a certain combination of coloured filters we can see white light again on the other side of the coloured filters.

2. Objects have substances in them called PIGMENTS. Because of these pigments, a certain object reflects a certain colour (or mixture of colours) out of the white light which shines on it. This reflected colour or mixture of colours is what we see. The other colours out of the same white light are absorbed (taken in) by the pigment in the object. These absorbed colours we do not see.

Evidence

Under green light, an object which appears red in while light appears black. Why? It is because there is no red light in the green light for the pigment in the object to reflect to our eyes. Instead, the pigment simply absorbs the green light. If the object was under white light, it would still absorb the green light (and other colours) out of the white light, but there would remain the red light out of the white light to be reflected.

3. In our eyes are special colour sensitive cells called CONES. There are three kinds of cones: red sensitive, green sensitive, and blue sensitive. These cones pick up the different colours of light which the objects reflect. All the colours we see, then, are the result of different combinations of red, green, and blue light. That is why these three are the primary colours of light.

Evidence

Scientists have examined the structure of the human eye and have done experiments while observing the way the eye works when colours are reflected to it.

ADDENDUM

A red pigmented object absorbs green and blue light and reflects red light.

A green pigmented object absorbs red and blue light and reflects green light.

A blue pigmented object absorbs red and green light and reflects blue light.

A yellow pigmented object absorbs blue light and reflects red and green light.

A purple pigmented object absorbs green light and reflects blue and red light.

A white pigmented object reflects red, green, and blue light.

A black pigmented object absorbs red, green, and blue light.